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AN INTRODUCTION
TO
GEOLOGY

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Scott

AN INTRODUCTION

TO

GEOLOGY

INNER GORGE OF THE GRAND CAÑON OF THE COLORADO. (U. S. G. S.)

Frontispiece

AN INTRODUCTION

TO

GEOLOGY

BY

WILLIAM B. SCOTT

BLAIR PROFESSOR OF GEOLOGY AND PALÆONTOLOGY
IN PRINCETON UNIVERSITY

"There rolls the deep where grew the tree.
O earth what changes hast thou seen!
There where the long street roars, hath been
The stillness of the central sea.

"The hills are shadows, and they flow
From form to form and nothing stands;
They melt like mists, the solid lands,
Like clouds they shape themselves and go."

TENNYSON.

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TO

A. A. P. S.

This Book is Dedicated

IN GRATEFUL RECOGNITION OF AN EVER READY
AND INSPIRING SYMPATHY

PREFACE

THIS book had its origin in the attempt to write an introductory work, dealing principally with American Geology, upon the lines of Sir Archibald Geikie's excellent little "Class-Book." In spite of vigorous efforts at compression, it has expanded to its present size, though the difference from the "Class-Book," in this respect, lies not so much in the quantity of matter as in the larger size of the type and illustrations.

The book is intended to serve as an introduction to the science of Geology, both for students who desire to pursue the subject exhaustively, and also for the much larger class of those who wish merely to obtain an outline of the methods and principal results of the science. To the future specialist it will be of advantage to go over the whole ground in an elementary course, so that he may appreciate the relative significance of the various parts, and their bearing upon one another. This accomplished, he may pursue his chosen branch much more intelligently than if he were to confine his attention exclusively to that branch from the beginning of his studies.

Students, and only too often their instructors, are apt to prefer a text-book upon which they can lean with implicit confidence, and which never leaves them in doubt upon any subject, but is always ready to pronounce a definite and final opinion. They dislike being called upon to weigh evidence and balance probabilities, and to suspend judgment when the testimony is insufficient to justify a decision. This is a habit of mind which should be discouraged; for it deludes the learner into the belief that he knows the subject when he has only acquired some one's opinions and dogmas, and renders further progress exceedingly difficult to him. In no science are there more open questions than in Geology, in none are changes of view more frequent, and in none, consequently, is it more important to emphasize the distinction between fact and inference, between observation and hypothesis. An open-minded hospitality for new facts is essential to intellectual advance.

The order in which the different sections of the book are taken up should depend somewhat upon the season of the year in which the study is begun. The chapter on the Rock-forming Minerals is intended rather for reference than for actual learning, and should at first be employed only to give the beginner a notion of what minerals are like and to familiarize him with a few of the commonest and most important kinds. The unfortunate likeness in the terminations of the names of so many minerals and rocks is a source of great confusion to the beginner. It is, therefore, important that he should have grasped the conception of what a mineral is, before commencing to deal with rocks. A repeated experience of this confusion has led to the wide separation of the chapter upon minerals from those treating of the rocks. It is perhaps hardly necessary to say that a knowledge of elementary inorganic Chemistry is indispensable to an understanding of almost any part of Geology, and especially of those parts which are concerned with the minerals and rocks.

If the course of study be commenced in the autumn, it will be well to take up first the chapters upon the Surface Agencies, or even the Structural Part, according to the opportunity for outdoor work and occasional excursions. When it is possible to undertake it, this work in the field should by no means be omitted. Even for those who have no intention of becoming geologists, observation at first hand possesses a far higher interest and charm and a much greater educational value than merely reading books or hearing lectures. Such observation is also a corrective of the false impressions which are necessarily given by the somewhat artificial and systematic treatment of a vast subject in a text-book. In many cases, it is impracticable for the teacher to take his class into the field. Under these circumstances he should constantly impress upon the minds of his pupils the inadequacy of all schemes and systems to embrace the great facts of nature, and should encourage them to observe for themselves, testing what they read by what they see.

In preparing this book, I have of course availed myself of material wherever it was to be found, but I wish to acknowledge my special obligations to the text-books of Dana, Le Conte, Geikie, Green, Prestwich, Credner, Kayser, Neumayr, Koken, de Lapparent, and Jukes-Brown. From the last-named writer is taken the arrangement of the Dynamical Agencies, which experience in the class-room has led me to consider as the best. Besides these general works, I have received great help from monographs and special articles by many writers, particularly from those by Clark, Cross, Dale, Dean, W. M. Davis, Gilbert, Harris, Kemp, Russell, Van Hise, Walcott, Willis, Weed, and others.

I take sincere pleasure in acknowledging the extremely kind and ready assistance which many fellow-workers in all parts of the country have granted me with unsparing liberality. Mr. Walcott, Director of the United States Geological Survey, has been especially kind in this respect, and has allowed the fullest use of the Survey's fine collection of photographs. The liberal way in which advantage has been taken of this permission is to be seen in the many illustrations in the following pages marked (U. S. G. S.), all of which were made from the Survey photographs. Many other members of the United States Geological Survey have spared no pains to help me in the work of compilation, with advice, information, papers, drawings, photographs, and every other means in their power. To these gentlemen my obligations are very great, and to Messrs. Walcott, Cross, Emmons, Gilbert, Hill, Weed, and Willis I wish to express my cordial thanks for many acts of kindly and most valuable assistance.

Professor J. F. Kemp was so kind as to send me the advance sheets of his "Lecture Notes on Rocks," of which extensive use has been made. Mr. A. Smith Woodward, Mr. Agassiz, Dr. Bashford Dean, and Professor I. C. Russell have kindly supplied me with illustrations from their books. Mr. Lucas of the U. S. National Museum, Dr. C. Hart Merriam of the U. S. Agricultural Department, Professor R. D. Salisbury, Professor Calvin of the Iowa Geological Survey, Mr. Pynchon of Hartford, and the officers of the Pennsylvania Railroad Company have furnished many valuable photographs. My colleagues, Professors Magie and Libbey, have assisted me with the proofs, and the latter has allowed the free use of his collection of unpublished photographs taken in Greenland, Alaska, and the Hawaiian Islands. Another colleague, Dr. A. E. Ortmann, has taken great pains in the selection of figures of the American fossil invertebrates, which have been redrawn by Mr. R. Weber, University Draughtsman. My friend, Dr. Baur, has been my guide through the tangled mazes of the synonymy of the American fossil reptiles. To these gentlemen, one and all, hearty gratitude is due for oft-repeated and unstinted kindness.

No one can be more conscious than the author of the very imperfect character of his performance, but he ventures to hope, nevertheless, that the book may find a place of usefulness, supplementary to the host of excellent works on Geology already in existence.

PRINCETON, N. J., Jan. 15, 1897.

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INTRODUCTION

Geology is the study of the earth's history and development, as recorded in the rocks, and of the agencies which have produced that development.

From this definition it appears that the central problem in geology is the deciphering of the earth's history, and that the historical standpoint is the dominant one. Geology deals with the earth as a cosmical unit, and is a great synthesis of all those sciences which throw light upon the structure of the globe and which may be used in interpreting its records. Astronomy, physics, chemistry, mineralogy, physical geography, zoölogy, and botany are all drawn upon for this purpose. The goal of our inquiries is the history of the earth *as a whole*, and not of a single continent merely. We should endeavour to gain a true insight into those great processes of development which control the whole visible universe, and which exhibit in the most impressive way the great principles of order and of uniformly acting laws. It is, however, necessary to make a selection from the immense body of ascertained facts, and it is clearly advantageous that, so far as possible, we should make use of our own country for this purpose. It must always be remembered that the instances chosen from familiar scenes are but illustrations and examples of world-wide processes and structures. To find active examples of some important phenomena, we must travel to far-distant lands, but even of these we shall find the unmistakable traces in our own continent, as having been at work here at one time or another in the past.

Geology is one of the most modern of the sciences. In the works of certain classical and mediæval writers we find, it is true, some descriptions of geological phenomena, and sound inferences were sometimes drawn from the facts. But no attempt was made to gather an extensive series of observations, or to construct a harmonious system of facts and inferences, and no one imagined that a connected history of the earth was within the bounds of human attainment. Before such a history could be written, it was necessary that the other physical and natural sciences should have reached a considerable degree of perfection; for geology, as we have seen, is a synthesis of these sciences. It was only in the latter part of the eighteenth century, that these other branches of knowledge had so far been perfected that they could offer to the geologist a firm foundation upon which to build the structure of his own science. The early workers in geology hardly attempted more than to ascertain the materials of which the earth is composed and the way in which those materials are put together. In carrying out this apparently simple task, it soon became evident that the present condition of the earth is the outcome of a long series of past changes, which must be understood if we would comprehend the earth's structure as it is now. The past must be studied in the light of the present, and the present in the light of the past, for each supplements and helps to explain the other.

Such a conclusion is repugnant to our instinctive feeling, that the earth is stable and well-nigh unchangeable, a feeling which finds expression in Bryant's familiar line: "The hills rock-ribbed and ancient as the sun." This very natural belief is due to the exceeding slowness with which the surface features of the globe are modified, so that in the brief span of human life the modifications are almost imperceptible. Generations of men live and die in the same spot, while the natural features of hill and rock, valley and plain, seem to remain exactly as they were. When, however, attention was at last directed to these changes, it was found that they were unceasing, and were especially noticeable in lands which, like the countries around the Mediterranean, had been occupied for many centuries by civilized men. Occasionally, too, great tempests or earthquakes or volcanic outbursts produced changes which could not but strike the most careless observer.

When once the fact was established that the solid globe was subject to change, men looked first to the more obvious and violent natural forces as the agents of this change. To the occasional destructive fury of the hurricane, the earthquake, and the volcano was attributed far greater importance than to the ceaseless but inconspicuous work of the rain and the river. Another reason why sudden and violent catastrophes were regarded as the only important factors of change, was the very general belief that the earth was only a few thousand years old. If all the modifications which the earth's surface has demonstrably undergone were effected within such a comparatively brief period, then they must have been accomplished suddenly and violently and, in great part, by agencies of which we have had no experience. Thus, all sorts of fantastic causes, such as collisions with comets' tails, were conjured up to account for the facts, and speculation ran riot.

The purely arbitrary character of these speculations and fancies rendered them unsatisfactory to thinking men. The progress of astronomy had gradually familiarized their minds with the idea of the almost infinite distances which separate the heavenly bodies, and with the conceptions of order and the uniform operation of law. These conceptions made the supposed cataclysms and convulsions of the earth's history seem unnatural and improbable, and led geologists to inquire whether simpler explanations could not be devised. This, in turn, led to the careful study of those modifications of the earth's surface which are still in progress. Gradually the conviction grew, that the agencies which are still at work upon and within the globe are the same as those which brought about the manifold changes of the past, and that the earth's history is one of vast and unimaginable length. Scholars made little progress in deciphering the Egyptian hieroglyphics until the discovery of the Rosetta Stone, with its bilingual inscriptions, furnished the key. So the geologists found that one key to the past was to be found in the study of the forces which may be observed in actual operation at the present time.

Another advance was made while the disputes regarding the nature of geological forces and the length of geological time were still in progress. In 1799 William Smith, an English engineer, announced the discovery that the order of succession of the rocks might be determined by means of the *fossils*, or remains of animals and plants, which they contain. This discovery was made possible by the advances in zoölogy, by means of which the different species could be accurately discriminated. Since the earliest recorded times, the animals and plants of the earth have been subject to continual change, and the degrees of change give us a standard of chronology, in accordance with which the various groups of rocks may be arranged in their order of succession. The archæologist makes a similar use of the coins, inscriptions, and objects of art, which he finds among the ruins of buried cities. These enable him to determine the races of men who built those cities and the dates at which they flourished, and to fix their place in the general history of civilization.

The lines along which geology has developed were nearly all laid down late in the last century, or early in the present one, but the progress of the science has led to many changes in men's conceptions of the subject, some of which changes have been revolutionary. Geology began with the study of western Europe, and on account of this narrowly restricted range of view, erroneous notions naturally crept into the new science. As the study has been extended to other continents, new and larger views have been gained, and doubtless, when the whole earth has been accurately examined, many of our present opinions will need revision, though we cannot hope ever to reach final certainty upon all points.

To many intelligent people this continual modification of scientific opinion, which is a necessary consequence of advancing knowledge, is a source of annoyance. This attitude of mind comes from a failure to discriminate between fact, and inference or hypothesis. Accurately observed facts may be added to, but they remain trustworthy: the changeable element is the inference which is drawn from the facts. These inferences are of very different degrees of certainty. Some such deductions which were made centuries ago remain unshaken to-day, while others of far more recent date have proved illusory. Thus, when we find a rock composed of cemented sand-grains, arranged in regular beds or layers, we infer that it was laid down under water, because of its exact resemblance to accumulations of sand which are forming under water to-day. If the sandstone be full of marine shells, we infer that it was formed under the sea, and further that the land where the rock is now found was once covered by the sea. Such inferences are practically certain, because they explain all the known facts and are in conflict with none. On the other hand, the hypotheses of Cuvier and others as to the character of the earth's development, and the manner in which the successive assemblages of animals and plants were called into being, were abandoned long ago.

In the process of reasoning from the known to the unknown, the inferences become the more uncertain, the farther we recede from demonstrable facts. Hypotheses are assumptions which we make to explain and coördinate large numbers of facts, and so long as their true nature is understood, they are useful, indeed indispensable, means of reaching the truth. The objection is that they are too often taught as though they were established beyond dispute. A true hypothesis will prove to be in harmony with newly discovered facts, which will take their place under it simply and naturally. A false hypothesis, on the other hand, may be in accordance with all the facts known at the time when it was proposed, but the progress of discovery will bring to light facts which are inconsistent with the hypothesis, until it is plainly seen to be inadequate and misleading. Yet even a false hypothesis may serve a useful purpose, for it puts before us a definite problem, instead of a mere catalogue of uncorrelated facts. The pathway of every science is strewn with wrecks of hypotheses which have been used, worn out, and thrown aside. In all our thinking and reasoning the distinction between hypothesis and fact must be steadily held in view.

While, in its most comprehensive sense, geology consists in the application of nearly all the physical and natural sciences to the elucidation of the earth's history, the geologist has his own special field of investigation. This he finds in the rocks, and every exposure of rocks yields him material. It might seem that, at best, his studies must be very superficial, and that he must soon eke out his scanty facts with daring guess-work. Such is happily not the case. The fact that rocks of different ages were formed in different places, and that great disturbances have so tilted immense bodies of rocks that their *edges* are exposed to view, enables the observer to study vast thicknesses of them, without descending below the surface of the ground. Seventy-five years ago Playfair saw and expressed this truth. "Men can see much further into the interior of the globe than they are aware of, and geologists are reproached without reason for forming theories of the earth, when all they can do is but to make a few scratches on the surface."

The history of the earth has been recorded, for the most part, upon *its successive surfaces*, and it is not necessary to penetrate deep into the interior of the globe. In later chapters we shall learn how these surfaces came to be buried to great depths and yet retained the characters impressed upon them when they were superficial in position, as written pages are buried under fresh accumulations of manuscript. This fact, together with the disturbances which have made the deep-seated rocks accessible to study, renders the task of deciphering the record less hopeless than might be imagined.

The study of geology must be carried on at first hand, and cannot be adequately learned from books alone. The use of books is to serve as guides in directing the learner in what to look for and to enable him to compare distant lands with his own. The arrangement and treatment of such a complex subject as geology cannot avoid a certain artificial character, which will surely mislead the student, unless he learns to observe and reason for himself. Some parts of our country are more favourable to geological study than others, but none is entirely devoid of geological interest, and the operations of the dynamical agencies may be watched everywhere. To one who thus familiarizes himself with the structure and history of the country, every landscape will offer a renewed charm and interest. The study of the rocks will lead him step by step to the widest outlook over the history of the earth, to the contemplation of infinities of energy, space, and time, bringing him at last face to face with the mystery of the Universe. To this inscrutable mystery every line of scientific inquiry must ultimately lead, for human knowledge is like a dim taper which illumines a little space, but is surrounded by immeasurable darkness.

The very diverse lines of inquiry which together make up the science of geology, must be classified and divided for the purposes of orderly treatment. The following are the principal divisions of the science.

1. **Dynamical Geology,** or the study of the forces which are now at work in modifying the surface of the earth, and of the chemical and mechanical changes which they effect. This is the key by which we may interpret past changes.

2. **Structural Geology,** or the study of the materials of which the earth is composed and of the manner in which they are arranged; together with such explanations of the modes in which the arrangement was produced, as may be inferred from the structure.

3. **Physiographical Geology** is an examination of the topographical features of the earth and of the mode in which they were produced. Primarily, this subject is a province of physical geography, but it is a valuable adjunct to geology.

The three foregoing divisions together constitute a larger division, which is called *Physical Geology*, and which is contrasted with —

4. **Historical Geology.** — This is the study of the earth's history and development, the changes of level between land and sea, of topography, of climate, and of the successive groups of animals and plants which have lived upon the globe. As we have seen, the historical is the dominant standpoint in geology, the main problem of which is to interpret the records of the earth's history. The other departments are to be regarded as the means to this great end.

CHAPTER I

THE ROCK-FORMING MINERALS

Of the simple, undecomposable substances, which chemists call elements, and of which somewhat more than seventy have been identified on the earth, only about twenty enter at all largely into the composition of the earth's crust,[1] so far as this is accessible to examination. It is estimated that 97 per cent of the crust is made up of ten elements.

Nonmetallic.		Metallic.	
Oxygen	O.	Aluminium	Al.
Hydrogen	H.	Potassium	K.
Silicon	Si.	Sodium	Na.
Carbon	C.	Calcium	Ca.
		Magnesium	Mg.
		Iron	Fe.

The remaining ten are far less abundant, but yet of considerable importance.

Chlorine	Cl.	Lithium	Li.
Fluorine	F.	Barium	Ba.
Sulphur	S.	Manganese	Mn.
Phosphorus	P.	Titanium	Ti.
Boron	B.	Zirconium	Zr.

Only two of these elements, carbon and sulphur, are found in a more or less impure state as minerals or rock masses; the others occur as compounds, formed by the union of two or more of them.

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[1] By crust of the earth is meant its exterior portion or shell of indefinite thickness. It does not necessarily imply any very radical difference from the interior, though the term was first employed to denote the solid external layer which covered a supposed liquid interior.

A *mineral* is a natural, inorganic substance, which has a homogeneous structure, definite chemical composition and physical properties, and usually a definite crystalline form.

Crystals are solids of more or less regular and symmetrical shape, bounded, usually, by plane surfaces. The number of known crystalline forms is already very great, and yet they may be all reduced to thirteen fundamental shapes, which are prisms, octahedrons (eight-sided), or dodecahedrons (twelve-sided).

The thirteen fundamental forms and their innumerable secondary derivatives fall into six systems, which are characterized by the relations of their axes. The *axes* of a crystal are imaginary lines, which connect the centres of opposite faces, or opposite edges, or opposite solid angles, and which intersect one another at a point in the interior of the crystal.

The Systems of Crystalline Forms have received many names, the following being those which are most generally used in this country: —

I. **Isometric System** (monometric, cubical, regular). — In this system the three axes are of equal length and intersect one another at right angles; it includes the cube, regular octahedron, and rhombic dodecahedron, forms which are symmetrical in all positions.

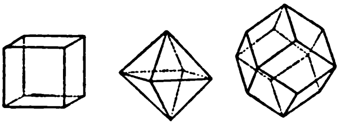

FIG. 1. — Forms of the Isometric System: Cube; Regular Octahedron; Rhombic Dodecahedron.

II. **Tetragonal System** (dimetric, pyramidal). — The axes intersect at right angles, but are not all of equal length; the two lateral axes are of equal length, but the vertical axis is longer or shorter than the laterals. Includes the right square prism and the square octahedron, the faces of which are isosceles triangles.

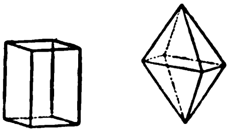

FIG. 2. — Forms of the Tetragonal System: Right Square Prism; Square Octahedron.

III. Hexagonal System. — Here four axes are employed, three equal lateral axes intersecting at angles of 60 degrees, and a vertical axis, which is perpendicular to and longer or shorter than the laterals. Includes the rhombohedron, hexagonal prism, and scalenohedron.

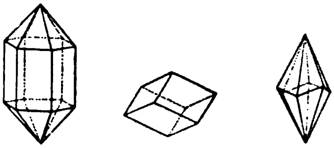

FIG. 3. — Forms of the Hexagonal System: Hexagonal Prism; Rhombohedron; Scalenohedron.

IV. Orthorhombic System (rhombic, trimetric). — The three axes intersect at right angles and are all of different lengths; rectangular and rhombic prisms, and rhombic octahedron.

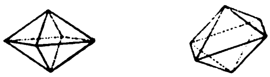

FIG. 4. — Forms of the Orthorhombic System: Rhombic Octahedrons.

V. Monoclinic System (monosymmetric, oblique). — All three axes are of different lengths; two of the axes, usually the laterals, are at right angles to each other, while the third is oblique: right rhomboidal and oblique rhombic prisms.

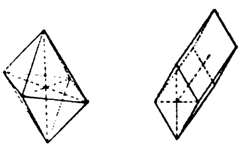

FIG. 5. — Forms of the Monoclinic System: Monoclinic Pyramid and Prism.

VI. Triclinic System (anorthic, asymmetric). — Three axes of unequal lengths and oblique to one another: oblique rhomboidal prism, doubly oblique octahedron.

It is important to bear in mind the relations which the fundamental forms sustain toward one another. For example, a regular octahedron may be derived from a cube by evenly paring off the eight solid angles, until the planes thus produced intersect one another, the centres of the faces of the cube becoming the apices of the solid angles of the octahedron. Conversely, a cube may be formed from an octahedron by symmetrically truncating the angles, until the planes thus formed intersect. By slicing away the twelve edges of a cube or an octahedron a dodecahedron will result. These crystalline forms are, therefore, so related as to be all derivable one from another, and the relations of their axes remain unchanged; all three forms may be assumed by the same mineral, and they thus properly belong in the same system. Similar relations may be observed between the crystalline forms of the other systems.

It might be supposed that the crystalline systems and the relations of their imaginary axes were merely mathematical devices to reach a convenient classification of forms. Such a conclusion would, however, be a very erroneous one. Crystalline form is the expression of molecular structure, and many of the physical properties of minerals are determined by their mathematical figure. It is clear that the physical properties which depend upon form are not inherent in the molecules of the mineral, but are conditioned by the way in which the molecules are built up into the crystal. Amorphous substances refract light equally in all directions, and are thus called *isotropic*; but when an amorphous substance crystallizes, it assumes the qualities proper to its crystalline form. Thus water is isotropic, while the hexagonal crystals of ice are singly refractive in only one direction, doubly refractive in two. The same substance may, under different circumstances, crystallize in different systems, and will then display the properties appropriate to each system.

Not only the refractive powers of a crystal, but also its mode of expansion when heated, and its conductivity of electricity and heat depend upon its form.

The crystals of the isometric system, which have their three axes of equal length, are singly refractive in all directions, expand equally when heated, and conduct heat and electricity equally in all directions. Those of the tetragonal and hexagonal systems, which have one axis longer or shorter than the others, are doubly refractive along the lateral axes, expand equally when heated, and show equal conductivity along these axes. Along the principal axis they are singly refractive, expand to a different degree when heated, and display a different conductivity along this axis than along the others. In the orthorhombic, monoclinic, and triclinic systems, which have all the axes of unequal lengths, the crystals are singly refractive in two directions; they expand unequally and conduct differently along all their axes.

The optical properties of minerals are of great value in the study of rocks, and by the aid of the polarizing microscope very minute crystals may be identified.

Most substances which are solid under any circumstances are capable of assuming a crystalline form, so that solidification and crystallization are usually identical. For the formation of large and regular crystals, it is necessary that the process be gradual and that space be given for the individual crystals to grow. Usually crystallization begins at many points simultaneously, and the crystals crowd upon one another, resulting in a mass of more or less irregular crystalline grains. The same substance which, when very rapidly solidified, forms an amorphous glass, will give rise to distinct crystals, if slowly solidified.

Crystallization requires that the molecules be free to move upon each other, and thus to arrange themselves in a definite fashion. It may take place either by the deposition of a solid from solution, by cooling from a state of fusion, or by solidification from the condition of vapour. In all cases the size and regularity of the crystals depend upon the time and space allowed for their growth. In a manner not yet understood, amorphous solids may be converted into crystalline aggregates. This has been observed in the case of certain glassy volcanic rocks, which, though amorphous when first solidified, have gradually become crystalline, without losing their solidity. This process is called *devitrification*.

The actual steps of crystallization may be observed by slowly evaporating a solution of some crystalline salt under the microscope. The first visible step in the process is the appearance of innumerable dark points in the fluid, which rapidly grow, until their spherical shape is made apparent. The globules then begin to move about rapidly and arrange themselves in straight lines, like strings of beads, and next suddenly coalesce into straight rods. The rods arrange themselves into layers, and thus build up the crystals so rapidly, that it is hardly possible to follow the steps of change. In certain glassy rocks, which solidified too quickly to allow crystallization to take place, the incipient stages of crystals, in the form of globules and hair-like rods, may be detected with the microscope.

Secondary Forms of Crystals. — A great variety of crystalline forms is produced by the occurrence of secondary planes or faces on the angles or edges of the primary forms. All the similar parts of the crystal may be modified in the same way, or alternating similar parts may be so modified.

Certain faces may be obliterated by the enlargement of others; but however great the variation, the angle at which corresponding faces meet almost invariably remains constant for each mineral.

Massive and imperfectly crystallized minerals may consist of grains, fibres, or thin layers (*laminæ*).

Hardness. — The hardness of minerals is a useful means of identifying them. For this purpose they are referred to a scale of hardness, ranging from such soft substances as may be readily scratched with the finger-nail, to the hardest known substance, diamond. The degree of hardness is expressed by the numerical place of the mineral in the scale, and intermediate grades are indicated by fractions. Thus a mineral which is scratched by quartz and scratches orthoclase with equal ease, has a hardness of 6.5. The scale is as follows: —

1. Talc.
2. Selenite.
3. Calcite.
4. Fluor-spar.
5. Apatite.
6. Orthoclase.
7. Quartz.
8. Topaz.
9. Sapphire.
10. Diamond.

Cleavage. — Many minerals split readily along certain planes, still retaining a crystalline form, while in other directions they break irregularly. This property is called *cleavage.* Cleavage is uniform in the different varieties of the same mineral, and takes place either in planes parallel to one or more faces of the *fundamental form* of the crystal, or along the diagonals of that form.

Pseudomorphs occur when one mineral assumes the crystalline form proper to another. This may take place either by the addition or the removal of certain constituents, or some constituents may be removed and others substituted for them. The entire substance of a mineral may be removed and its place taken, molecule by molecule, by another, retaining the form, sometimes even the cleavage, of the first. The study of pseudomorphs is often of the greatest service, as throwing light upon the history of the rock in which they occur.

Compound crystals are formed by the joining of simple crystals. When two half-crystals are united along a plane in such a way that their faces and axes do not correspond, they are said to be twinned. When the twinning is repeated along numerous parallel planes, the crystal is a *polysynthetic twin.* Two crystals united at the ends to form a right angle, are called *geniculate,* while two geniculate crystals may be so combined as to form a cross, and then are said to be *cruciform.*

Crystals of the same form may vary in length and in the size of their corresponding faces, which gives rise to numerous irregularities of shape.

Rock-forming Minerals. — The number of known minerals is exceedingly great, and is constantly increasing, but only a few enter in any important way into the constitution of the earth's crust. We now proceed to a consideration of these constituent minerals, which are called rock-forming minerals, because the rocks are aggregations of them. It must be emphasized that the student can gain no real knowledge of minerals or rocks by merely reading about them; it is necessary that he should familiarize himself with actual specimens.

A. MINERALS COMPOSED OF SILICA

Next to oxygen, silicon is by far the most abundant constituent of the earth's crust, though never occurring alone. It is united with oxygen to form silica (SiO_2) or enters into the formation of more complex compounds. The oxide, silica, is the commonest mode of occurrence and forms the most abundant of all the minerals.

1. **Quartz** (SiO_2) is anhydrous silica in a crystalline state; it belongs in the hexagonal system, and crystallizes in hexagonal prisms capped by six-sided pyramids, or in double six-sided pyramids, or in modifications of these forms. It is insoluble in any acid except hydrofluoric, and only very slowly soluble in boiling caustic alkalies. When dissolved, as may be done by somewhat complicated processes, silica shows a distinct acid reaction.

Quartz has no cleavage and is very hard ($H = 7$), scratching glass readily, while it cannot be scratched with a knife; the specific gravity (sp. gr.) is 2.6.

When pure and symmetrically crystallized, quartz is transparent, colourless, and lustrous (rock crystal), but it more commonly is found in dull masses. Different varieties are coloured by metallic oxides: thus, *amethyst* is quartz stained purple by the oxide of manganese; *smoky quartz*, or *cairngorm*, owes its brownish or yellowish colour to the oxide of iron; and there are many other kinds.

In its various forms quartz is the most abundant of minerals, and plays the most important part in the formation of the different classes of rocks.

2. **Chalcedony** occurs in spheroidal or stalactitic masses, composed of more or less concentric shells. The structure is crystalline, and displays radiating fibres, which are perpendicular to the shells. The chemical composition and behaviour of this mineral are the same as in quartz, but the specific gravity is somewhat lower (2.59–2.64), and the optical properties different. Chalcedony has a waxy appearance, and is translucent or semi-opaque, and of various pale colours.

3. **Opal, Hyalite.** Hydrated silica (SiO_2, xH_2O). — These minerals are amorphous and have no crystalline form. Opal is either translucent or opaque and of various colours. Precious opal (a gem) and common opal differ in colour, and in the fact that the former is iridescent, the latter not. Hyalite is colourless and transparent. Hydrated silica is lighter than the anhydrous (sp. gr. = 2.2) and more readily soluble in hot alkaline waters. These minerals are of much less importance as constituents of rock than the forms of quartz.

4. **Agate** is a banded mineral, composed of layers of amorphous and crystalline silica, chalcedony, jasper, amethyst, rock crystal, etc.

5. **Flint** and **Chert** are also believed to be mixtures of hydrated and anhydrous silica. They occur in amorphous masses of neutral or dark colours, and are opaque, or somewhat translucent in thin pieces.

B. MINERALS COMPOSED OF SILICATES

Silica is an acid and forms a very extensive series of compounds with various metallic bases. As rock-forming minerals the silicates are second only to the silica minerals in importance.

I. THE FELSPAR GROUP

The felspars are essentially silicates of alumina (Al_2O_3) together with potash, soda, or lime. Three primary felspars occur: *orthoclase*, a potash felspar ($K_2O, Al_2O_3, 6\,SiO_2$); *albite*, a soda felspar ($Na_2O, Al_2O_3, 6\,SiO_2$); and *anorthite*, a lime felspar ($2\,CaO, 2\,Al_2O_3, 4\,SiO_2$). From the combination of these primary minerals two series are formed: the lime-soda series, *oligoclase*, *andesine*, and *labradorite;* and the potash-soda series, as yet imperfectly known.

The felspars crystallize in either the monoclinic or triclinic systems, but the forms of the crystals are very much alike. With few exceptions, these minerals are of pale colours and, except when decomposing, are very hard.

1. *Monoclinic Felspars*

Orthoclase is a potash felspar ($K_2O, Al_2O_3, 6\,SiO_2 = K, Al, Si_3O_8$), though soda may replace part of the potash, and small quantities of lime and iron are usually present. Hardness = 6, sp. gr. = 2.54–2.57. Orthoclase crystallizes in oblique rhombic prisms and is very generally twinned; there are two sets of cleavage planes, which intersect at a right angle and have thus given its name to the mineral. Orthoclase is usually dull and turbid, which is due to the presence of various alteration products, and even thin sections under the microscope are commonly hazy. *Sanidine* is a glassy, transparent variety of orthoclase, which is found in lavas of late geological date. Its clearness is due to the absence of the decomposition products, which render ordinary orthoclase turbid.

2. *Triclinic Felspars*

The minerals of this series are grouped together under the comprehensive term of *Plagioclase*, because of the difficulty of distinguishing them from each other under the microscope; they are very generally characterized by polysynthetic twinning, which makes fine parallel lines on the basal cleavage planes. Chemically, they are soda, lime, or lime-soda felspars, of which the latter are isomorphous mixtures of albite and anorthite. The following table (from Lévy and Lacroix) gives the composition of the various members of this series, representing the soda-felspar constituent, or *albite*, by Ab, and the lime-felspar constituent, or *anorthite*, by An: —

NAME.	COMPOSITION.	SPECIFIC GRAVITY.
Albite	Ab	2.62
Oligoclase	$Ab_{10}An_3$	2.65
Andesine	Ab_2An_1	2.67
Labradorite	Ab_2An_3	2.70
Anorthite	An	2.75

It will be observed that the specific gravity increases with the lime constituent, and the fusibility diminishes in the same proportion. Anorthite is decomposed by hydrochloric acid, labradorite is slightly attacked by it, while the other members of the series are not affected.

Anorthoclase is a triclinic potash-soda felspar (Ab_2Or_1), but is not a common constituent of rocks.

II. THE FELSPATHOID GROUP

These minerals are very closely allied to the felspars in chemical composition, but differ from them in crystalline form and physical properties. They have a much more restricted distribution than the felspars, but have, nevertheless, an important bearing upon the classification of certain groups of rocks in which they occur.

Nepheline is a silicate of potash, soda, and alumina ($(Na, K)_2O$, Al_2O_3, $2\,SiO_2$). It crystallizes in transparent and colourless six-sided prisms, of the hexagonal system. H = 5.5–6; sp. gr. 2.6. The mineral is soluble in hydrochloric acid, gelatinous hydrated silica separating out. It is an important constituent of certain lavas.

Leucite is composed as follows: K_2O, Al_2O_3, $4\,SiO_2$, with some of the potash replaced by soda. It crystallizes in twenty-four-sided figures (trapezohedrons), which belong to the tetragonal system, but can be distinguished from the isometric only by very careful measurement. H = 5.5–5.6; sp. gr. = 2.44–2.56. It is slowly attacked by hydrochloric acid.

Leucite cannot be called a common mineral, but its significance will be better seen when we come to take up the study of rocks.

Analcite. — This mineral is usually regarded as a decomposition product, and placed among the zeolites (see below, p. 21); but recent investigations make it very probable that in some cases, at least, analcite is a mineral of primary origin. Its composition is: Na_2O, Al_2O_3, $4\,SiO_2$, $2\,H_2O$. Crystallizes in the isometric system, and is colourless in transmitted light. It is soluble in mineral acids, with separation of gelatinous silica. Sp. gr. = 2.15–2.28.

III. The Mica Group

These minerals have a complex chemical composition, and are so variable that it is difficult to give formulæ for them; they are silicates of alumina, together with potash, lithia, magnesia, iron, or manganese. There is a difference of opinion regarding the crystalline system to which the micas should be referred. When crystallized, they all form six-sided prisms, but there are reasons for believing that this is a false symmetry. Usually certain micas are referred to the hexagonal, and others to the orthorhombic systems, but some authorities regard them all as monoclinic. All varieties have a remarkably perfect cleavage, and split into thin, elastic, and flexible leaves, by which they may be readily recognized. They are quite soft, and most of them may be scratched with the finger-nail.

1. **Muscovite** may be selected as the most important and wide-spread of the numerous alkaline micas, it being a hydrated potash-mica, with the general formula, K_2O, $3\,Al_2O_3$, $6\,SiO_2$, $2\,H_2O$. It is a lustrous, silvery-white mineral, usually transparent and colourless in thin leaves; it has a specific gravity of 2.76–3.1, and a hardness of 2.1–3.

Sericite is a silvery or pale green form of muscovite, which is an alteration product and often is derived from a felspar.

2. **Lepidolite** is a mica in which part of the potash has been replaced by lithia.

3. **Biotite** is the most important and widely disseminated of the numerous dark-coloured, ferromagnesian micas. This mineral is black or dark green in mass, and smoky even in thin leaves; chemically it is a hydrated silicate of potash, alumina, iron, and magnesia. In hardness and specific gravity it differs little from muscovite.

IV. THE AMPHIBOLE AND PYROXENE GROUPS

These two groups contain parallel series of minerals of similar chemical composition, but differing in their crystalline form and physical properties. In composition they are silicates of various protoxide bases, and range from silicates of magnesia to those of lime and lime-alumina, while silicate of iron is present in most of them. In crystalline form they belong to the orthorhombic and monoclinic systems, and can be distinguished by their cleavage. The pyroxenes have a prismatic cleavage of nearly 90°, while in the amphiboles the angles are 124° 30′ and 55° 30′. The orthorhombic amphiboles are rare and unimportant as rock-forming minerals, but the pyroxenes of this form are widely distributed, though less so than the monoclinic.

a. *Orthorhombic Pyroxenes* are silicates of magnesia and iron (Mg, Fe)O, SiO_2.

1. **Enstatite** has less than 5% of FeO.

2. **Bronzite** has 5–14% of FeO.

3. **Hyperstheme** has more than 14% of FeO.

The colour becomes darker and the optical properties change with the increase in the percentage of iron.

b. *Monoclinic Pyroxenes.*

1. **Augite.**—This very abundant and important mineral is a silicate of lime, magnesia, iron, and alumina (Ca, Mg, Fe)O, $(Al, Fe)_2O_3$, 4 SiO_2. Sp. gr. = 3.3–3.5; H = 5–6. It crystallizes in oblique rhombic prisms, and in colour is green to black and opaque.

2. **Diallage** is a variety of augite, usually of a green colour, which is distinguished by its laminated structure, with lustrous faces.

c. *Monoclinic Amphiboles.*

1. **Hornblende,** like augite, which it closely resembles in chemical composition, is among the most important of rock-forming minerals. In colour it is usually green, brown, or black, and it crystallizes in modified oblique rhombic prisms. Sp. gr. = 2.9–3.5; H = 5–6.

2. **Tremolite** is a silicate of magnesia and lime (CaO, MgO), SiO_2. This mineral is pale green or white and occurs in laminæ or long, blade-like crystals.

3. **Actinolite** resembles tremolite in composition, with the addition of iron (CaO, MgO, FeO) SiO_2. Colour, green; sp. gr. = 3–3.2; usually occurs in long and thin crystals. *Asbestus* is a fibrous variety of tremolite or actinolite, in which the fibres are often like flexible threads and may be woven into cloth.

V. THE OLIVINE GROUP

Olivine is the only mineral of this group of sufficient importance to require mention; it is a silicate of magnesia and iron 2 (MgO, FeO)SiO_2, though the percentage of iron varies greatly.

Sp. gr. = 3.2–3.5; H = 6.5–7. Olivine crystallizes in the orthorhombic system, and occurs in prisms, flat tables, or irregular grains. Hydrochloric acid decomposes the mineral, with separation of gelatinous silica. The colour varies from olive green to yellow, or it may be colourless, and usually the irregular grains look like fragments of bottle glass.

C. OTHER SILICATES, CHIEFLY DECOMPOSITION PRODUCTS

Many of the complex silicates, when long exposed to the action of the weather and of percolating waters, become more or less profoundly changed. One of the commonest of these changes is hydration, or the taking up of water into chemical union, and this may be accompanied by the loss of soluble ingredients, or the replacement of some constituents by others.

I. Zeolites

In this group are included a large number of minerals, which are hydrated silicates of alumina, potash, soda, lime, etc. They all contain large quantities of water and hence boil and effervesce when heated before the blowpipe. All these minerals are products of decomposition and do not occur as original constituents of rocks.

II. Talc and Chlorite Groups

1. **Chlorite.** — Under this name are grouped a number of closely allied minerals, which are hydrated silicates of alumina, magnesia, and iron. They are soft minerals, with a hardness of 1–1.5 and a specific gravity of 2.6–2.96, and are of a green colour. The crystalline form is somewhat uncertain, but is now generally regarded as monoclinic, with a pseudo-hexagonal symmetry. These minerals are laminated and split readily into thin leaves, as do the micas, from which they may be distinguished by the fact that the leaves are not elastic.

The chlorites result from the decomposition of hornblende, augite, or the magnesian micas.

2. **Talc** is a hydrated silicate of magnesia, $3\,MgO, 4\,SiO_2, H_2O$; the water varies in amount to as much as 7%. Sp. gr. = 2.56–2.8; H = 1. It is of a white or pale green colour, with a pearly lustre and a greasy, soapy feeling to the touch. Talc is rarely found crystallized; the crystals have a false hexagonal symmetry, and it is doubtful whether they should be referred to the orthorhombic or monoclinic systems. Usually it occurs in flakes or foliated masses, which split into thin, non-elastic leaves. Talc results from the alteration of magnesian minerals.

3. **Steatite,** or Soapstone, has the same composition as talc, but is not foliated, and may be much harder, as much as 2.5.

4. **Serpentine** is a hydrated silicate of magnesia and iron: $3\,(MgO, FeO)\,2\,SiO_2, 2\,H_2O$. It does not crystallize, except sometimes in pseudomorphs. Sp. gr. = 2.5–2.65; H = 2.5–4. Its proper colour is green, but it is usually mottled with red or yellow by iron stains. Serpentine is generally formed from the decay of olivine, less commonly from augite, or hornblende.

Kaolinite is the hydrated silicate of alumina, $Al_2O_3, 2\,SiO_2, 2\,H_2O$. It is usually soft and plastic, but orthorhombic crystals of pseudo-hexagonal symmetry may be sometimes detected with the microscope. Kaolinite arises from the decomposition of the felspars and especially of orthoclase.

Glauconite is a hydrated silicate of alumina and iron, with small quantities of lime, magnesia, potash, and soda. It is of a green colour, soft and friable, and results largely from the decay of augite.

D. CALCAREOUS MINERALS

1. **Calcite,** carbonate of lime, $CaCO_3$. Sp. gr. = 2.72; H = 3. This mineral crystallizes in the hexagonal system, in a great variety of forms; rhombohedrons and scalenohedrons are common; hexagonal prisms and pyramids less so. Cleavage is very perfect, parallel to the faces of a rhombohedron, and the mineral breaks up into rhombohedrons when struck a sharp blow. Calcite is rapidly attacked, even by cold and weak acids, CO_2 escaping with effer-

vescence. When pure, as in Iceland spar, the mineral is colourless, very transparent and lustrous, and displays the phenomenon of double refraction strongly; but more commonly it is cloudy or white, or stained red or yellow by iron. The decomposition of silicated minerals containing lime gives rise to calcite, and as this is soluble in water holding CO_2, nearly all natural waters have more or less of it in solution. It is widely diffused among the rocks, and in a state of varying purity forms great masses of limestone.

2. **Aragonite** ($CaCO_3$) is a somewhat harder and heavier form of calcite, with a specific gravity of 2.93 and a hardness of 3.5–4, and crystallizes in compound prismatic forms which belong to the orthorhombic system. It has not the marked cleavage of calcite and is very unstable; when heated it is converted into calcite and falls into tiny rhombohedrons of that mineral.

3. **Dolomite** is a carbonate of lime and magnesia, $(Ca, Mg)CO_3$, but with variable proportions of the two bases; it resembles calcite in appearance, and crystallizes in rhombohedrons which often have curved faces. Sp. gr. = 2.8–2.9; H = 3.5–4. Dolomite may be readily distinguished from calcite by the fact that cold acids affect it but little.

4. **Selenite,** hydrated sulphate of lime, $CaSO_4, 2H_2O$. Sp. gr. = 2.31–2.33; H = 1.5–2. It crystallizes in right rhomboidal prisms, belonging to the monoclinic system, and cleaves into thin non-elastic leaves. When pure, selenite is transparent and colourless, but is often stained by iron. This mineral occurs largely in granular masses, called *gypsum,* from which plaster of Paris is made by calcining the gypsum and so driving off the water of crystallization. Gypsum is slightly soluble and is present in most natural waters. *Alabaster* is a gypsum of especially fine grain, mottled in pale colours, or white.

5. **Anhydrite,** $CaSO_4$, is sulphate of lime without water; it is harder and heavier than gypsum (Sp. gr. = 2.9–2.98; H = 3–3.5), and crystallizes in a different system, the orthorhombic. The crystals have three sets of cleavage planes, which intersect each other at right angles.

6. **Apatite** is a phosphate of lime, with chloride and fluoride of calcium, which vary in relative amounts, $3(Ca_3P_2O_8), 2(Ca, Cl, F)$. Sp. gr. = 2.92–3.25; H = 5. It crystallizes in hexagonal prisms, terminated by hexagonal pyramids, and also occurs in masses. The original and unchanged mineral is transparent and colourless, changing on alteration to opaque brown or green. Apatite is soluble in acids, and in water containing carbon dioxide, or ammonia; it is thus dissolved out of the rocks and widely diffused in the soils, where it forms a valuable plant food.

7. **Fluor-spar**, fluoride of calcium, CaF_2. Sp. gr. = 3.01–3.25; H = 4. Crystallizes in the isometric system, usually in cubes, and has a perfect octahedral cleavage. When pure, fluor-spar is clear and colourless, but it is more commonly stained blue, green, yellow, or brown.

E. IRON MINERALS

1. **Hæmatite,** or Specular Iron, is ferric oxide, Fe_2O_3. Sp. gr. = 4.5–5.3; H = 6.5. Crystallizes in rhombohedrons, or more commonly, in nodular masses, which are composed internally of very flat crystals. The colour is black or steel-grey, which becomes red when the mineral is finely powdered. Hæmatite frequently contains earthy and other impurities and is one of the most important ores of iron.

2. **Limonite,** or Brown Hæmatite, is hydrated ferric oxide ($2\ Fe_2O_3, 3\ H_2O$) containing more than 14 % of water. It is softer than hæmatite and of a yellow or brown colour. Sp. gr. = 3.6–4; H = 5–5.5.

3. **Magnetite** is the black oxide of iron, Fe_3O_4 (or FeO, Fe_2O_3). Sp. gr. = 4.9–5.2; H = 5.5–6.5. Crystallizes in the isometric system, usually in octahedrons, sometimes in dodecahedrons. This mineral is strongly magnetic and is black in colour, with a bluish-black metallic lustre, when viewed in reflected light. Magnetite is widely diffused in certain classes of rocks, and also occurs in veins and beds, which form an important source of supply of the metal.

4. **Ilmenite** is a titaniferous ferric oxide, $(Ti, Fe)_2O_3$. Sp. gr. = 4.5–5.2; H = 5–6. When crystallized, this mineral is rhombohedral, but is generally massive.

5. **Siderite** is ferrous carbonate, $FeCO_3$. Sp. gr. = 3.7–3.9; H = 3.5–4.5. Crystallizes in rhombohedrons, the faces of the crystals frequently much curved, and often the crystals are very much flattened. When fresh, the mineral is grey or brown. It is but slightly acted on by cold acids; hot acids dissolve it with effervescence. Mixed with clay, siderite forms clay iron-stone, a valuable ore.

6. **Iron Pyrites,** bisulphide of iron, FeS_2. Sp. gr. = 4.9–5.2; H = 6–6.5. Crystallizes in the isometric system, usually in cubes, sometimes in dodecahedrons, and has a very characteristic brassy lustre and colour, to which it owes the popular name of "fools' gold." It is very hard, cannot be scratched with a knife, and strikes fire, like flint, when struck with steel. The mineral is soluble in nitric acid: it is widely disseminated in the rocks.

7. **Marcasite,** or White Iron Pyrites, has the same composition as pyrites, but crystallizes in the orthorhombic system, in modified prisms, but more commonly occurs in nodular masses, with a radial structure. It has the same hardness as pyrites, but is not quite so heavy. Sp. gr. = 4.68–4.85. In colour it is paler than pyrites, with a tendency to grey, green, or even black. It decomposes very readily and after a few months' exposure, even to dry air, often crumbles to a whitish powder.

The iron minerals are seldom largely represented in any given rock, with the exception of the ore beds, but iron is one of the most widely diffused of substances, few rocks being altogether free from it, and its various compounds play a very important rôle as colouring-matter in the rocks. Ferrous carbonate gives no colour to the rock in which it occurs, and such rocks are apt to have a blue or grey tint, due to other substances, both organic and inorganic. When such rocks are exposed to the action of air and moisture, ferric oxide and ferric hydrates are formed, the former giving a red colour and the latter various shades of yellow and brown.

A blue clay containing ferrous carbonate will, when fired in a kiln, give rise to red bricks or pottery, by the conversion of $FeCO_3$ into Fe_2O_3. Exposure to moist air produces a similar effect in nature, and the contrast in colour between the superficial and deep-seated layers of the same rock is often as great as between blue clay and red brick.

Weathered blocks stained red on the outside are often blue, grey, or nearly black on the inside, the change not having penetrated through the whole mass. Such changes are most conspicuous in the sandstones, because their porous character allows a comparatively free circulation of air and water through them, but similar effects are frequently to be observed in other rocks also.

PART I

DYNAMICAL GEOLOGY

We have already seen that the chief task of geology is to construct a history of the earth, to determine how and in what order the rocks were formed, through what changes they have passed, and how they reached their present position. The logical order of treatment might seem to require that we should first learn what the rocks are, of what they are composed, and how they are arranged, before attempting to explain these facts. In such a study, however, we should meet with so much that would be quite unintelligible, that a more convenient way will be to begin with a study of the agencies which are at work upon and within the earth, and which tend to modify it in one or other particular. In other words, we must employ the present order of things as a key by means of which to decipher the hieroglyphics of the past, and proceed from what may be directly observed to past changes which can only be inferred.

We might assume that the present was so radically different from the far-distant past, that the one could throw no light upon the other. Such an assumption, however, would be most illogical, for there is nothing to support it. There is no reason to imagine that physical and chemical laws are different now from what they have always been, and the more we study the earth, the more clearly we perceive that its history is a continuous whole, determined by factors of the same sort as are now continuing to modify it. Some geologists assume that these agencies have always acted with just the same intensity as they do to-day; but this assumption is neither necessary, nor in itself probable. There is, on the contrary, much reason to believe that while certain forces act with greater efficiency at the present time than they did in the past, others act with less.

An attentive examination of the changes which are now in progress on the surface of the earth, will show us that nothing terrestrial is quite stable or unchangeable, but that there is a slow, ceaseless circulation of matter taking place on the surface and within the crust of the globe. Matter, chemistry teaches us, is indestructible, and, disregarding the relatively insignificant amount of material which reaches us from outer space in the form of meteorites, the sum total of matter composing the globe remains constant. But while practically nothing is added to or taken away from the materials which make up the earth's crust, ceaseless cycles of change continually alter the position, physical relations, and chemical composition of those materials. This circulation of matter may be aptly compared to the changes which take place in the body of a living animal, only, of course, they are of a different kind and are effected at an infinitely slower rate. In the animal body, so long as life lasts, old tissues break down into simpler compounds and are gotten rid of, while new tissues are built up out of fresh material. So, on the earth rock masses decay, their particles are swept away, accumulate in a new place, perhaps far distant from their source, and are consolidated into new rocks, which in their turn are attacked and yield materials for further combinations. The study of the physical and chemical changes in the bodies of animals and plants constitutes the science of physiology, and by analogy we may call dynamical geology the physiology of the earth's crust. Analogies, however, must not be pushed too far, or they land us in absurdities. One essential difference between the earth and a living organism suggests itself at once, namely, that the former is self-contained, and neither ejects old material nor receives new, but employs the same matter over and over again in ever-varying combinations. The animal or plant, on the contrary, continually takes in new material from without, in the shape of food, and ejects the waste resulting from the breaking down of tissue.

Although the earth needs no fresh supplies of matter, its dynamical operations are, to a very large extent, maintained by energy from without; namely, from the sun. The circulation of the winds and waters, the changes of temperature, and the activities of living beings, all depend upon the sun's energy, and were that withdrawn, only such changes as are brought about by the earth's internal heat could continue in operation.

The study of dynamical agencies, subterranean and surface, necessarily gathers together an enormous mass of detail. But we need concern ourselves with only so much of this as throws light upon the earth's history, so that the sciences of dynamical geology and physical geography, though having much in common, are essentially distinct. In order to make clear the operations of the forces which tend to modify the surface of the earth, it is necessary that we should classify and arrange them, so that they may be treated in a more or less logical order. However, in making such a classification, it is impossible to avoid entirely a certain arbitrariness of arrangement, since we must consider separately agencies that act together. Natural phenomena are not due to single causes, but to combinations and series of causes, and yet, to make them intelligible, they must be treated singly or in simple groups, else we shall be confronted by a chaotic mass of uncorrelated details. The career of a raindrop, from its first condensation to its entrance into the sea through the mouth of some river, is a continuous one, yet rain and rivers are distinct geological agencies and do different kinds of work. Again, the very important way in which the various dynamical agents modify, check, or augment one another, must not be overlooked in a systematic arrangement of these agents.

Some of the agencies that we shall consider may seem, at first sight, to be very trivial in their effects, but it must be remembered that they appear so only because of the short time during which we observe them. For enormously long periods of time they have been steadily at work, and their cumulative effects must not be left out of account in estimating the forces which have made the earth what we find it.

Much as may be learned by the study of the operation of the forces which are still at work in modifying the earth, this method of study is yet insufficient to solve all geological problems. Many of the changes which have indisputably taken place are such as no man has ever observed, because they are brought about so slowly or so deep down within the crust that no direct observation is possible, and we can only infer the mode of procedure by examining the result. No human eye has ever witnessed the birth of a mountain range, or has seen the beds of solid rock folded and crumpled like so many sheets of paper, or observed the processes by which a rock is changed in all its essential characteristics; "metamorphosed," as it is technically called. All such problems must be discussed in connection with structural geology.

The dynamical agencies may, primarily, be divided into two classes: I, *the Subterranean Agencies*, which act, or at least originate, at considerable depths within the earth; and II, *the Surface or Superficial Agencies*, whose action takes place at or near the surface of the earth. The former are due to the inherent energy of the earth, and their seat is primarily subterranean, though their effects are very frequently apparent at the surface. These agencies are also called *igneous* (from *ignis*, fire), which is a misnomer; but the term is nevertheless in common use.

The logical order of treatment of these subjects is to begin with the subterranean agencies, because the most ancient rocks of the earth's crust were doubtless formed by these forces, and the circulation of matter upon and through the crust started originally from *igneous rocks*, made by cooling at the surface of a molten globe.

SECTION I

SUBTERRANEAN OR IGNEOUS AGENCIES

CHAPTER II

INTERIOR CONSTITUTION OF THE EARTH—VOLCANOES

No problems of geology are more difficult and obscure than those connected with the internal constitution of the earth, and satisfactory explanations of the subterranean agencies have not yet been devised. This is because the interior of the earth is so completely beyond the range of direct observation. The deepest boring is hardly more than $\frac{1}{4000}$ part of the earth's radius, and data derived from the temperature observations of such shallow openings leave a great deal to conjecture. The enormous pressures also which obtain within the mass of the globe, are such that we can form but inadequate conceptions of their effects.

Temperature of the Earth's Interior. — Volcanoes, which eject white-hot and molten lavas, and thermal springs, which pour out floods of warm or even boiling water, plainly indicate that the interior of the earth is highly heated, at least along certain lines. Direct observations tend to prove that this high temperature is universally diffused through the mass of the earth. At the surface of the ground and for a short distance below it, the temperature varies, like that of the air, though to a less degree, between day and night and between different hours of the day. Farther down, the daily variation ceases, but there is a difference of temperature at different seasons, it being lower in winter than in summer. As in the case of the superficial layer, the range is less extreme than in the air. Penetrating still deeper, we come to a level where the temperature remains the same throughout the year, and is also the same as the *annual average* temperature of the air at the same locality above ground. This shows that the temperature at this level of no variation is determined by the solar heat and other climatic factors. The depth at which this level is situated depends upon the latitude of the place where the observation is made. At the equator it is only three or four feet below the surface of the ground, while in the polar regions it is said to be several hundred feet below. This does not imply that the effects of the sun's heat penetrate less deeply at the equator than at the poles, but that the small variations of atmospheric temperatures in the tropics are equalized at shallow depths within the earth. In temperate regions this level occupies an intermediate position, and at the latitude of New York is found at a depth of about fifty feet.

Beneath the level of no variation the temperature increases with the depth, though at very different rates in different localities. Increasing heat with increasing depth is observed in all deep mines, tunnels, and borings, and in some cases the high temperature is a very effective barrier against any further penetration of deep shafts. In locating the great tunnels under the Alps the engineers have been compelled to exercise great care, lest temperatures exceeding those in which men can work should be encountered. The average rate of increase of temperature is usually put at 1° Fahrenheit for every 55 to 60 feet of descent, but recent observations made in the very deep shafts of the Calumet mine in the Lake Superior copper region, indicate that this rate is perhaps too high. Should this rate be continued regularly, it would give at a depth of 25 to 30 miles a heat sufficient to melt almost any rock, *at atmospheric pressures*.

Physical State of the Earth's Interior. — Astronomers and geologists agree in the opinion that the earth, at one stage in its history, was a nebulous mass, and that it has reached its present state by cooling and contraction. When, however, we attempt to determine how far solidification has proceeded, and what the present condition of the earth's interior is, we encounter great difficulties. On this subject three principal hypotheses have been proposed. (1) That the earth is practically a liquid body, covered only by a relatively thin solid crust. (2) That it is substantially solid, and may or may not contain localized enclosures of molten matter within it. (3) That it has a very large solid nucleus and a solid crust, and interposed between the two a layer of fused matter, upon which the crust floats in equilibrium.

In the present extremely imperfect state of knowledge it is not possible to decide definitely between these conflicting theories. The first, or "thin crust theory," is now almost entirely abandoned, for the known facts do not require us to believe that the increase of temperature downward keeps on indefinitely. It may well be the case that the globe has a uniform temperature from the centre to within a few miles of the surface. If this be true, we should observe the same increasing heat, the more deeply the crust is penetrated. Again, there is reason to believe that most rocks expand on melting, and thus the great pressures found deep within the earth would necessitate a higher temperature to melt a given rock at a given depth than at the surface. We do not know how far the temperature must be raised to overcome the increased pressure. More important are the astronomical objections, according to which the behaviour of the earth is like that of a rigid and not of a fluid body.

The second hypothesis, that the earth is solid to the centre, is held by many geologists and by most astronomers. The evidence in its favour is chiefly the fact already stated, that the globe behaves, in its astronomical relations, like a rigid solid. This view is not at all incompatible with the belief that considerable masses of fused material may be contained at various depths within the earth.

The third hypothesis, which postulates the presence of a fused layer between the crust and the nucleus, is held by many geologists and astronomers. According to this view, the earth first solidified at the centre from pressure, and it has even been suggested that the *molten* (as distinguished from the nebulous) part never exceeded a superficial layer of fifty miles in thickness. The next step was the formation of a solid crust at the surface by cooling, leaving beneath it a layer which is not under sufficient pressure to be consolidated, and, being protected by the crust, has not yet cooled to the point of solidification. Hence, the transition from one layer to another is gradual and not abrupt. Such an hypothesis is believed to avoid, on the one hand, the astronomical objections to a substantially fluid earth, and, on the other, certain geological difficulties in the way of accepting the belief that the earth is practically solid throughout. But, unfortunately, we are yet far too ignorant to decide between these different views, and it is merely a question of greater or less probability, according to the available evidence.

The subterranean or igneous agencies may be conveniently classified under four main heads: (1) volcanoes, (2) thermal springs, (3) earthquakes, (4) changes of level between land and sea. Of these, the second, including thermal springs, geysers, and the like, will be considered in a later chapter, because they are mixed agencies, and cannot be well understood until we have learned something of ordinary springs and their operations.

I. VOLCANOES

A volcano is usually a conical hill or mountain, having an opening, through which various molten or solid materials are cast up. The essential part of the volcano is the opening or vent, which establishes a connection with the highly heated interior of the globe. The mountain, when present, is secondary, and is formed by the materials which the volcano itself has piled up; it is thus the effect and in no sense the cause of the phenomena.

Present Distribution of Volcanoes. — The geographical distribution of volcanic vents has greatly changed at different periods of the earth's history. There are few large land areas which do not display traces of former volcanic activity, though such action may have died out ages ago, never to be renewed, and no active vent be found for great distances around the now extinct centres.

We cannot definitely determine the number of vents which are at present in activity in various regions of the earth, because a volcano may remain dormant for centuries, and then break out again. Almost all tradition of the volcanic nature of Vesuvius had died away among the inhabitants of Italy, until the dreadful eruption of the year 79 A.D. showed that it had only been slumbering. Many volcanic regions, such as the western part of North and South America, and the East Indian islands, have been known to civilized man for only a few centuries, and in such regions the distinction between dormant and extinct vents cannot always be made.

Furthermore, the number of vents is constantly changing, new openings forming, and old ones closing up, while some that had escaped observation are not infrequently discovered. Another distinction which is often arbitrary, is that between independent volcanoes and mere subsidiary vents connected with larger ones. Several submarine volcanoes have been observed, but it is altogether probable that many more exist which have escaped detection. Making these allowances, the number of volcanoes now active may be estimated at about 328, of which rather more than one-third are situated in the continents, and the remainder on islands.

The active volcanoes are not scattered hap-hazard over the surface of the globe, but are arranged in belts or lines, which bear a definite relation to the great topographical features of the earth. Two of these belts together encircle the Pacific Ocean; one on the west coast of the Americas runs from Alaska to Cape Horn, the other, a very long and sinuous band, running from Kamchatka through the islands parallel to the east coast of Asia, the East Indian and south Pacific islands, to the Antarctic circle, where it joins the American band.

A third band occupies a ridge in the eastern bed of the Atlantic, from Iceland to St. Helena, from which arise numerous volcanic islands and submarine vents. South of Iceland there are no known volcanoes for a great distance, until the Azores are reached, and on the east coast of the Americas are none at all. A subsidiary volcanic belt passes through the Mediterranean to Asia Minor, and others are those on the east and west coasts of Africa and in the Indian Ocean. The prevalent trend of the belts is thus in a generally north and south direction.

A very striking fact is the nearness of almost all active volcanoes to the sea; by far the greater number of vents are upon islands, and those of the continents are, with few exceptions, not far from the coasts. Another relation which should be noted, is that between the volcanic bands and the mountain chains, the bands running parallel to or coinciding with the mountains, as in the great volcanoes of the Andes. Not all coast lines or all mountain chains have volcanoes associated with them, but where the mountains are near the seashore, volcanoes are usually, though not invariably, found. The seat of volcanic activity is frequently shifted, as we have learned, and it has been observed that this activity tends to die out of the older rocks and to make its appearance in those of a later date.

Volcanic Eruptions. — The phenomena displayed by different volcanoes, or even by the same volcano at different times, vary greatly. It often seems difficult to believe that similar forces are involved, and that the divergences are due merely to different circumstances attending the outbreak. A careful comparison, however, of the varying phenomena brings to light a fundamental likeness in them all. Some vents, like Stromboli in the Mediterranean, are in an almost continual state of eruption of a quiet kind; others, like Vesuvius, have long periods of dormancy, broken by eruptions of terrible violence. In a general way, it may be said that the longer the period of quiet, the more violent and long-continued will the subsequent eruption be, while weak eruptions and those of short duration recur at brief intervals.

The comparatively gentle operations of Stromboli give the observer an opportunity to learn what are the essential phenomena of a volcanic eruption. Though occasionally breaking out with violence, Stromboli is for long periods in such exact equilibrium that barometric changes have a marked effect upon its activity, and the Mediterranean sailors make use of it as a weather-signal. The floor of the crater is formed by hardened lava, the cracks in which glow at night, with the heat of the molten mass below, and which is perforated by various openings. From some of these steam is given out, from others molten lava wells up occasionally. In openings of a third class the lava may be seen rising and sinking, until a great bubble forms on its surface and bursts with a loud roar, scattering the hardened lava scum about the crater, in fragments of various sizes, some very fine, others coarse. The bubble proves to be of steam, and when set free, the steam globule rises to join the cloud which always overhangs the mountain. The bursting of the steam bubble is followed by a rush of steam through the mass of the lava, the pressure is relieved, and the lava column sinks down out of sight, until the steam pressure again accumulates and the performance is repeated.

Evidently, one active agent in these phenomena is imprisoned steam in its struggles to escape. Different as are the manifestations at other volcanoes, steam is an important cause of the eruption in all cases, though the conditions under which it acts vary widely. Little or no combustion is involved, and that not as a cause, but as an effect of the activity.

In Vesuvius essentially the same phenomena may be observed, but on a far grander and more terrible scale. Earthquakes usually announce the coming eruption, increasing in force until the outbreak occurs. Terrific explosions blow out fragments of all sizes, from great blocks to the finest and most impalpable dust. The finer fragments arise chiefly from the scattering of the partly hardened lava by the force of the explosion, but in part also from the crashing together of the blocks as they rise and fall through the air. Inconceivable quantities of steam are given off with a loud roar, which is awe-inspiring in its great and steady volume. The condensation of such masses of vapour produces torrents of rain, which, mingling with the "ashes" and dust, gives rise to streams of hot mud that flow for long distances and are often exceedingly destructive. Great floods of molten rock, or lava, issue from the crater, or burst their way through the walls of the cone, and pour down the mountain side, until they gradually stiffen by cooling.

The first recorded eruption of Vesuvius is that which occurred in 79 A.D. and is described in two letters written to Tacitus by the younger Pliny. In this frightful paroxysm little or no molten lava was ejected, but the old cone was partly blown away (its remnant now forms the outer ring, called Monte Somma), and so enormous was the quantity of ashes that at Misenum, across the bay of Naples, the sun was darkened, as Pliny reports, "not as on a moonless cloudy night, but as when the light is extinguished in a closed room . . . In order not to be covered by the falling ashes and crushed by their weight, it was often necessary to rise and shake them off." Herculaneum was overwhelmed with floods of ashes mixed with water, while Pompeii was completely buried in dry ashes and small fragments.

This first historical eruption of Vesuvius was thus of the type known as *explosive*, which is exhibited in its extreme form by several of the East Indian volcanoes, and preëminently by Krakatoa, the eruption of which in 1883 was the most frightful ever recorded. This volcanic island, situated in the Strait of Sunda, was little known, except that it had been in eruption in 1680. As the island was uninhabited, the earliest stages of the outburst were not observed, but on May 20 a great cloud of steam was seen over the vent. The catastrophe occurred in August, when, besides the fearful devastation caused by the disturbances of the sea on the coasts of Sumatra and Java, the island itself was almost annihilated. Hardly one-third of its original surface was left above water, and where formerly was land are now depths of 100 to 150 fathoms of water. The force of the explosion produced waves in the atmosphere which were propagated around the whole earth, and the first one was observed in Berlin ten hours after the explosion.

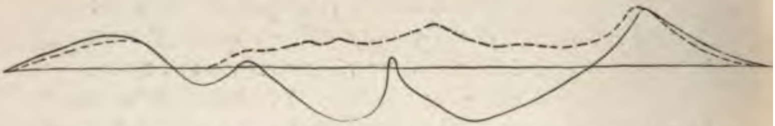

FIG. 6.—Profiles of Krakatoa. The full line is the present condition, the dotted line the condition before the eruption of 1883. (Judd.)

The ejected materials were all fragmentary and of an incredible volume; ashes were distributed over an area of 300,000 square miles, the greater part falling within a radius of eight miles around the island; stretches of water that had had an average depth of 117 feet were so filled up as to be no longer navigable. Enormous masses of pumice floated upon the sea and stopped navigation except for the most powerful steamers.

These tremendous explosions, even when they do not tear out one whole side of the mountain, as in the case of Krakatoa and Monte Somma, may blow off the top and thus leave a great crater ring many miles in circumference, within which subsequent eruptions may build up a new cone. When the volcanic activity dies out, the ring may be filled with water, forming a circular lake.

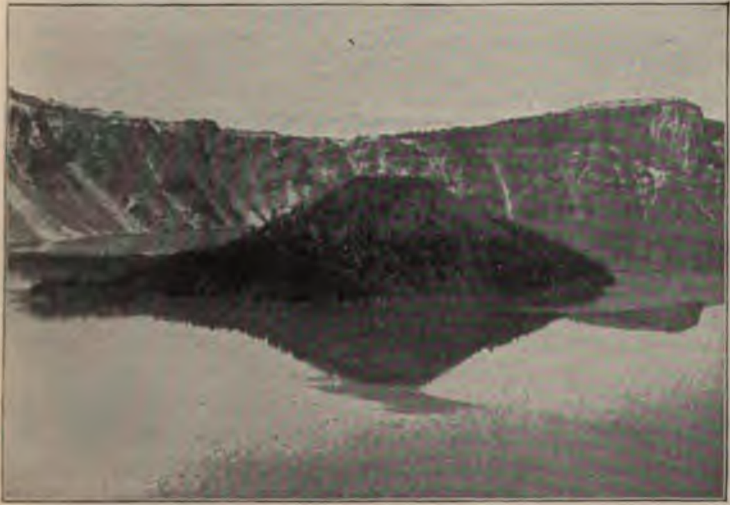

FIG. 7.—Crater Lake, Oregon. This crater ring is believed to have been formed by a draining away of the lava from below, and not by explosion. (U. S. G. S.)

Just the opposite extreme from these explosive eruptions is to be found in the volcanoes of the Sandwich Islands, such as Mauna

Loa and Kilauea. Here the eruptions are usually not heralded by earthquakes; the lava is remarkably fluid and simply wells up over the sides of the crater, pouring down the sides of the mountain in streams which flow for many miles. More commonly the walls of the crater are unable to withstand the enormous pressure of the lava column, and the molten mass breaks through at some level below the crater, rising through the fissure in giant fountains, sometimes 1000 feet high. Even in the ordinary activity of Kilauea jets of 30 and 40 feet in height are thrown up. Hardly any ashes or other fragmental products are formed, but the clouds of steam, the invariable accompaniments of volcanic outbursts, are present.

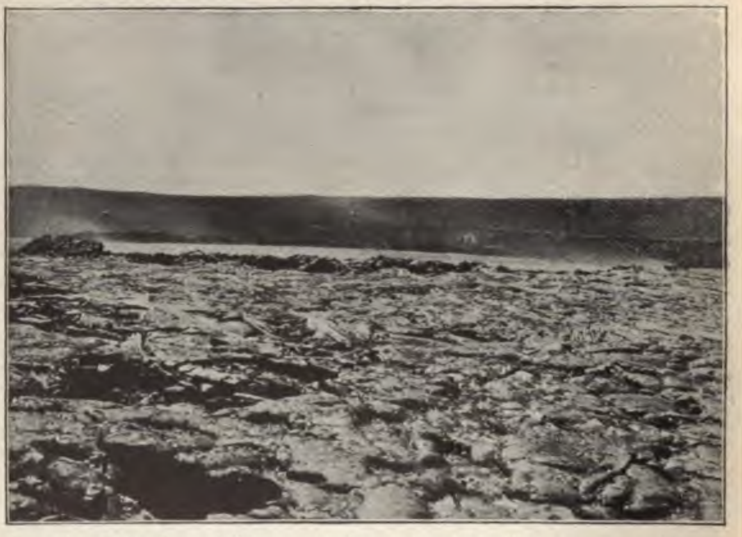

FIG. 8.—Crater-floor of Kilauea, showing the lava lake, Hale-mau-mau. (Photograph by Libbey.)

Between such extremes as the Hawaiian volcanoes, on the one hand, and the explosive East Indian type (Krakatoa), on the other, we may find every intermediate gradation. Everywhere imprisoned steam appears to be an important agent, while the differences are due to the varying degrees of accumulated pressure, the resistance to be overcome, the character of the lava, the manner in which the steam is generated, and similar factors.

Volcanic Products.—These form the most important part of the subject from the geological point of view, because they contribute largely to the permanent materials of the earth's crust. We meet with such materials of all geological ages, sometimes developed on a vast scale. The study of volcanic products is the key which enables us to comprehend the great group of rocks which are called igneous, though, as we shall see later, by no means all of these were poured out on the surface of the ground.

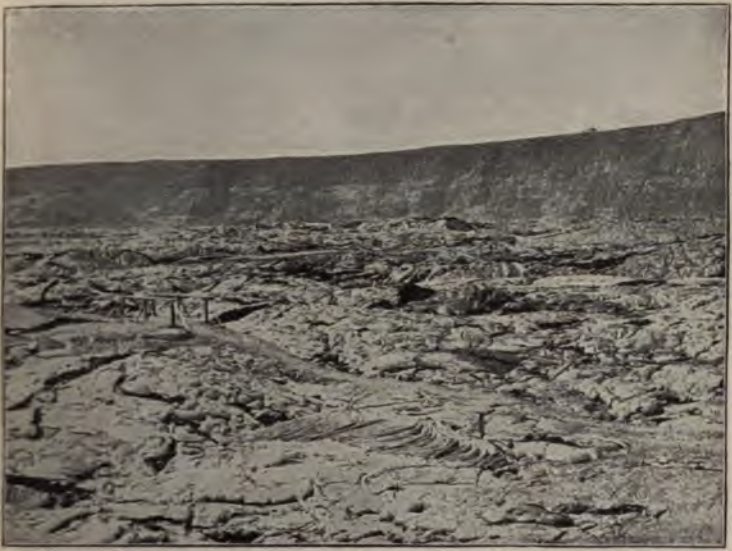

FIG. 9.—Another view of the crater-floor and walls of Kilauea. (Photograph by Libbey.)

Volcanic products are of three kinds: (1) *lava*, or molten rock; (2) *fragmental material*, including blocks, lapilli, bombs, the so-called volcanic ashes, cinders, and the like; (3) *gases and vapours.*

(1) *Lava.*—A lava is a more or less completely melted rock; the degree of fluidity varies greatly in different lavas, but is rarely, if ever, perfect. Instead of being a true liquid, a lava ordinarily consists of larger and smaller crystals, embedded in a pasty mass, which is saturated with steam and gases. The degree of fluidity depends upon several factors, the most obvious of which is temperature; the more highly heated the mass is, the more perfectly will it be melted. The quantity of imprisoned gases and vapours present has also an important effect, and some lavas appear to owe nearly all their mobility to these vapours. A third and most significant factor is the chemical composition. Those lavas which contain high percentages of silica (SiO_2), the *acid lavas*, are much less readily fusible than the *basic lavas*, in which the percentage of silica is lower. The difference in the proportion of silica present

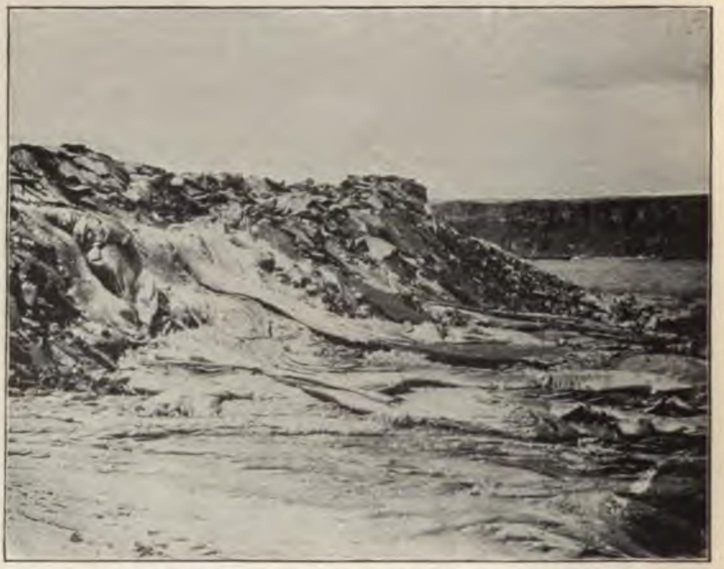

FIG. 10.—Edge of Hale-mau-mau, showing the ropy forms of the highly fluid lava, when cooling. (Photograph by Libbey.)

is associated with other chemical differences which have a similar effect upon fusibility, the basic kinds having much more lime, magnesia, and iron in them, which act as fluxes.

The experiments of Barus on the fusibility of lavas, which he divides into three groups, resulted as follows: (1) Certain lavas fuse readily (2250° F.); these are of basic composition and are made up of lime-soda felspars (see p. 16),[1] the augitic and allied ferro-magnesian minerals (p. 20), and iron oxide, but rarely have quartz (p. 15). (2) A second group is of medium fusibility (2520° F.), and is made up of lime-soda felspars, augitic or hornblende minerals, and frequently quartz. (3) The third series melt with difficulty (2700° F.), and remain pasty at even 3100° F. These

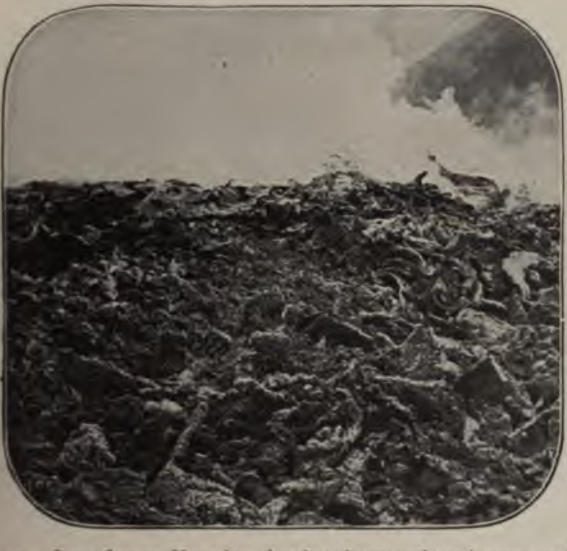

FIG. 11. — Lava flow on Vesuvius, showing slaggy and scoriaceous surface.

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[1] For the sake of convenience, the minerals are all considered together in Chapter I, but the student will greatly facilitate his acquaintance with them by referring to the description of every mineral that he finds mentioned in the text, and especially by examining specimens.

are acid lavas, and are composed of potash felspars (p. 16), with quartz, hornblende, or mica. Lavas which, like those of the Sandwich Islands, are notably fluid, are always of basic composition.

When a lava stream reaches the surface of the ground, the imprisoned vapours immediately begin to escape and the surface of the molten mass to cool and harden. The surface layers are blown by the steam bubbles into a light, frothy or slaggy consistency, forming "scoriæ" or cindery masses. The motion of the lava breaks up this thin crust into loose slabs and blocks, and on the advancing front of the stream these loose masses rattle down over one another in the wildest confusion. The less perfectly fused lavas are soon covered with heaped-up cindery blocks, while the more completely fluid lavas are characterized by curiously twisted, ropy surfaces, such as may be observed in the slag from an iron furnace.

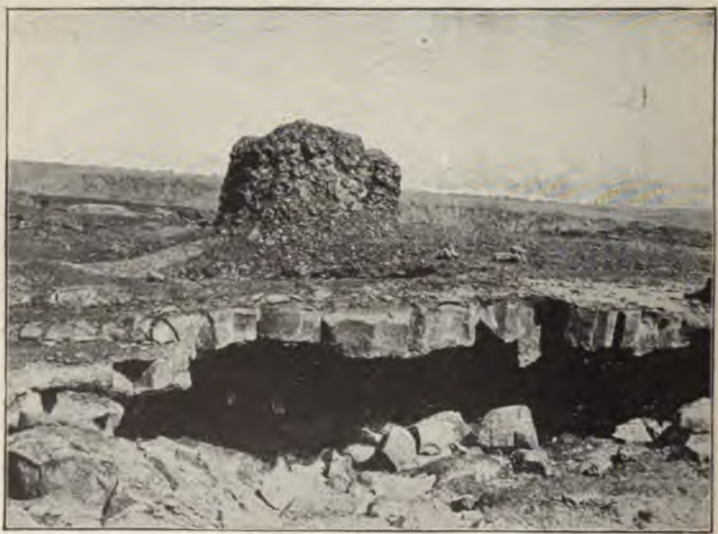

FIG. 12.—Lava-tunnel, and "Spatter-cone" formed by escaping steam, Kilauea. (Photograph by Libbey.)

The front of a lava stream advances, not by gliding over the ground, but by *rolling*, the bottom being retarded by the friction of the ground and the top moving faster, so that it is continually rolling down at the curved front end and forming the bottom. Thus, the scoriæ, though formed mostly on the top of the stream, are rolled beneath it, and the whole is enclosed in a cindery envelope. Or the flow may be checked by the mass of cinders, until the fluid lava bursts through them in a fresh stream. The scoriaceous mass is a non-conductor of heat, and greatly retards the cooling of the interior mass, which may remain hot for many years. The arched surface of cindery blocks may become self-supporting, and then the still fluid mass will flow away from beneath it, leaving long tunnels or caverns. These tunnels are especially well shown in Iceland and the Sandwich Islands.

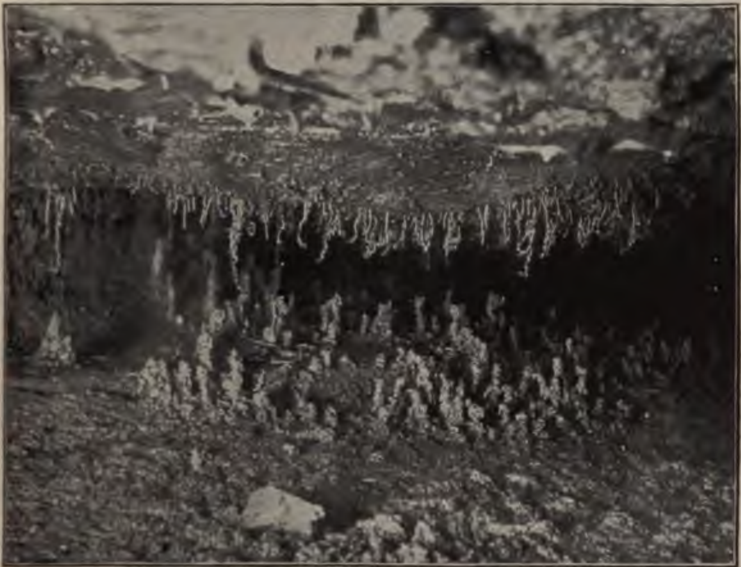

FIG. 13.—Lava stalactites and stalagmites, in lava-tunnel, Kilauea. (Photograph by Libbey.)

The distance to which lava streams extend and the rapidity with which they move are determined by the abundance and fluidity of the lava and the slope over which it flows. Some lavas are so liquid that they flow for many miles, even down moderate slopes, while others are so pasty that they stiffen and set within a short distance of the vent, even on steep grades. Ordinarily the motion soon becomes very slow, though thoroughly melted masses pouring down steep slopes may, for a short time, move very swiftly. One of the lava floods from Mauna Loa moved fifteen miles in two hours, and for shorter distances much higher rates of speed have been observed; but this is very exceptional.

The cooling of the surfaces of the lava stream takes place rapidly, while the interior cools but slowly, and great thicknesses require very long periods of time to become entirely cold. The differences in the rate of cooling produce very strongly marked varieties in the appearance and texture of the resulting rock. The portions which have chilled and solidified very quickly are glassy and form the volcanic glass, *obsidian*. If the swiftly cooling portions have been much disturbed by the bubbles of steam and vapours, they are made light and frothy; in some cases, as in pumice, they will float upon water. Otherwise, the glass is solid and is usually very dark in colour, resembling an inferior bottle glass in appearance. Microscopic examination shows minute, hair-like bodies in the glass, which are called *crystallites*, and represent the incipient stages of crystallization.

Passing inward from the surface of the lava stream, we find the steam bubbles becoming rarer, until they cease altogether, the vapours having escaped while the lava was still so soft that the bubble holes soon collapsed. At the same time the glassy texture of the rock is replaced by a stony character, which the microscope shows to be due to the formation of crystals too minute to be recognized by the unaided eye. Still deeper in the rock the stony texture passes gradually into an obviously crystalline one; and the slower the cooling, the larger will these crystals be, though in lava streams which have cooled on the surface of the ground, the whole mass, even of the deeper parts, is never coarsely crystalline.

Large crystals are, it is true, very often found in lavas, but these were formed before the ejection of the mass from the volcano. Such crystals frequently contain enclosures of glass, which indicate that the crystallization went on while the surrounding mass was still fluid. The edges and angles of these crystals are often corroded by the action of the melted portion of the lava, and the motion of the stream often cracks them. These facts go to prove that the large crystals were complete when the lava, as a whole, was still fluid and in motion. Stromboli ejects great numbers of perfect crystals of augite, which must have existed in the molten lava of the vent. The lavas which contain large crystals embedded in a fine stony or glassy base are said to be of a *porphyritic texture.*

It is important to remember that all these various textures may be found in one continuous rock mass, and bear witness as to the circumstances under which each part cooled and solidified. These textures also recur again and again in ancient rocks and enable us to determine their volcanic origin. The processes of rock destruction have in many cases laid bare deep-seated masses which were plainly once melted like true lavas, but which have cooled very slowly and under great pressures. In such rocks the texture is usually coarsely crystalline and shows no traces of glass or scoriæ. Between the surface lava flows and such deep-seated reservoirs every form of transition may be traced, often in continuous rock masses.

Where several successive lava flows issue from one vent, at intervals which allow one stream to be consolidated before the next is poured out over it, a rough bedding or stratification results, each flow being perfectly distinguishable when seen in section. Deceptive resemblances to the true stratification of sedimentary rocks (see p. 145) may thus arise, especially when the exposed section is short. But the wedge-like form of the sheets, the absence of bedding within the limits of each flow, and the nature of the rock itself, always enable us to distinguish these masses from the sediments which have been stratified by the sorting power of water.

A mass of lava, when it cools and solidifies, necessarily contracts, and since the cohesion of the mass is insufficient to allow it to contract as a whole, it must crack into blocks, separated by fine crevices, which are called *joints*. The mutual relations of the jointing planes, and the consequent shape of the blocks, are determined largely by the grain of the lava and its degree of homogeneousness. In fine-grained (and some coarse-grained) homogeneous lavas the jointing is apt to be very regular, and to give rise to prismatic or columnar blocks, which are usually hexagonal. This shape is due to the fact that the formation of hexagons requires less expenditure of work than other figures, and is produced by the intersection of systems of three cracks, radiating from equidistant points at angles of 120°. The long axes of the prisms are at right angles to the cooling surface. Starch and fire-clay, which shrink on drying, joint in the same way. The

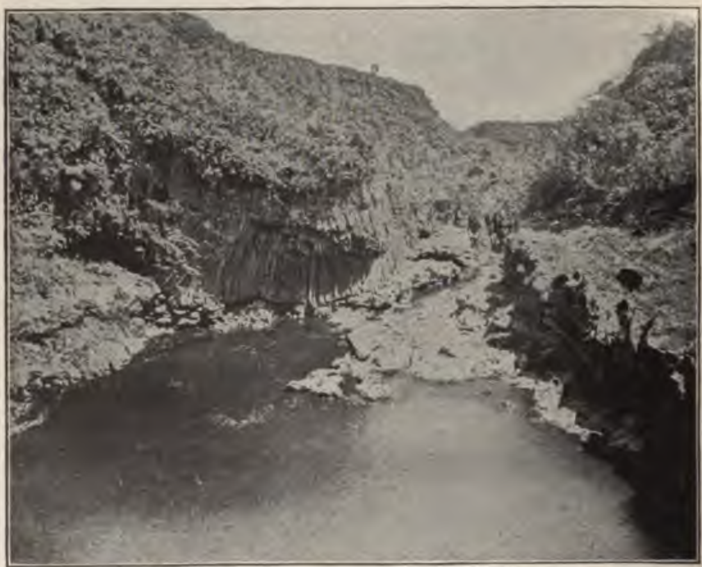

FIG. 14.—Stream gorge, island of Hawaii; displaying modern columnar lava. (Photograph by Libbey.)

coarser and more heterogeneous lavas usually break up into blocks of irregular size and shape.

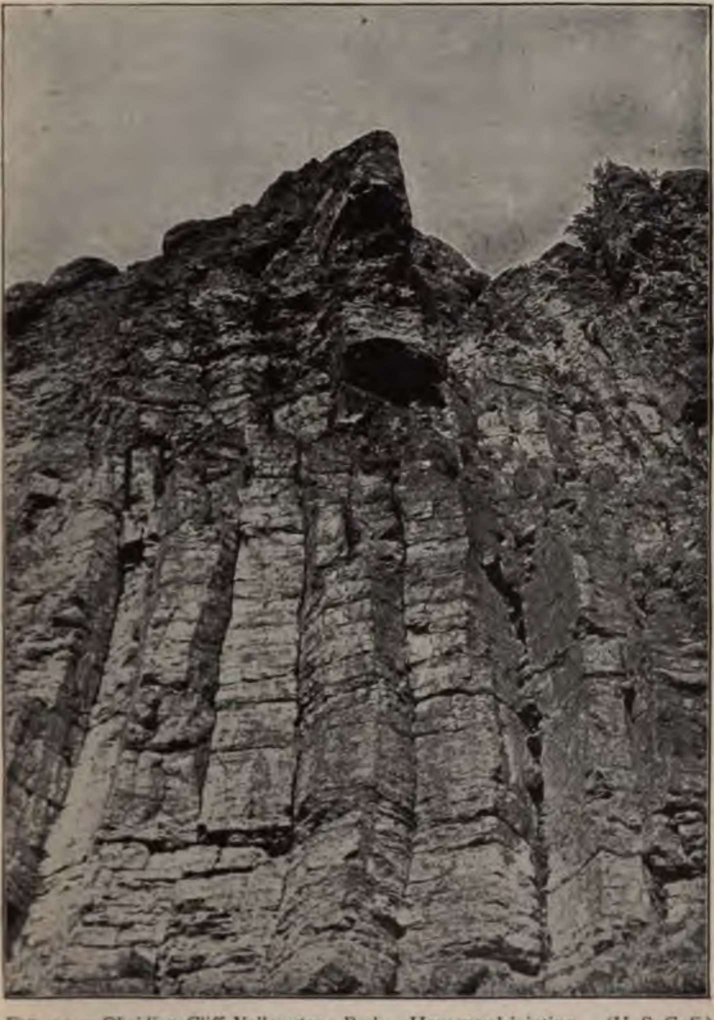

FIG. 15. — Obsidian Cliff, Yellowstone Park. Hexagonal jointing. (U. S. G. S.)

It must not be inferred that the joints of all rocks are due to shrinkage on cooling. It will be shown in a subsequent chapter that such is very far from being the case.

Not all the lava produced in and around a volcanic vent can reach the surface. Some of it may be forced horizontally between the beds of the surrounding rocks, thus forming *intrusive sheets*, which, when exposed in section, may be readily distinguished from surface flows by the fact that they have consolidated under pressure, and hence have no slag or scoriæ associated with them. Other portions of the lava will fill up vertical fissures in the volcanic cone or in the underlying rocks, and, solidifying in these fissures, form *dikes*. Such a fissure, twelve miles in length and filled with molten lava, was observed by Sir Charles Lyell in the neighbourhood of Ætna. In the great eruption of Skaptar Jokul (Iceland) in 1783 lava was poured out at several points along a line two hundred miles long, and doubtless this was a great lava-filled fissure which consolidated into a dike.

We thus see that the molten masses may not all well up through the crater of a volcano, but will seek egress along the line of least resistance, wherever that happens to be, breaching the walls of the volcanic cone, rising up through vertical fissures, or forcing their way as intrusive sheets between the beds of pre-existing rocks. In these various situations the different rates of cooling produce many varieties of rocks, though the original molten mass may have been nearly or quite identical in all of them.

Lavas which flow into the sea from a terrestrial vent, or are poured out from a submarine one show, as a rule, but little difference from those which solidified on land, because the rapid formation of a cindery crust will protect the hot lava from contact with the water. Sometimes, however, the sudden chill will cause the lava to disintegrate into a mass like black sand.

(2) *Fragmental Products.*—This division includes all the materials which are ejected from the volcano in a solid state. These are of all sizes and shapes, from huge blocks weighing many tons, down to the most impalpable dust, which the wind will carry for

thousands of miles. The very large blocks are commonly fragments of the older rocks, through which the volcanic vent has burst its way, tearing a great hole and scattering the fragments widely. For fifteen miles around the lofty volcano of Cotopaxi in Ecuador lie great blocks of this nature, some of them measuring nine feet in diameter.

More important and much more extensively formed and widely spread are those fragmental products which are derived from the lava itself. The more violently explosive the eruption, the greater the proportion of the lava that will be blown into fragments. In such eruptions as that of Krakatoa, all of it is thus dispersed and none remains to form lava flows. Cindery fragments thrown out of the vent are called *scoriæ*, while portions of still liquid lava thus ejected will, on account of their rapid rotation, take on a spherical form and are called *volcanic bombs*. *Lapilli* are smaller, rounded fragments, and *volcanic ashes* and *dust* are very fine particles, though with a wide range of variation in size. The term *ashes* is so far unfortunate, that it implies combustion, but nevertheless it accurately describes the appearance of these masses.

In the immediate neighbourhood of the vent fragments of all sizes accumulate, but the farther we get from the volcano, the smaller do the fragments become. The coarser masses around the vent form a *volcanic agglomerate*, in which the fragments are of all shapes and sizes, heaped together without any arrangement. More regular sheets of large angular fragments form *volcanic breccia*, and these may be seen on a grand scale in the Yellowstone National Park, and in many other parts of the Rocky Mountain region. The finer accumulations of ash, formed at a greater distance from the vent, are roughly sorted by the air and often quite distinctly divided into layers. The torrents of rain, which so frequently accompany volcanic outbursts, gather up the finer particles, forming sheets and streams of hot mud, which on drying sets into quite a firm rock, called *tuff* or *tufa*. Herculaneum lies buried under a solid mass of such tuff more than sixty feet deep, and hence is much less accessible than Pompeii, which is covered with scoriæ, lapilli, and ashes.

As volcanoes so generally stand in or near the sea, and as the lighter fragments, such as pumice, often drift for months upon the water before they sink, while the finer dust is carried vast distances by the wind, it would naturally be expected that volcanic materials should have a very wide distribution upon the sea-bottom. Such, indeed, proves to be the case, and this kind of material, laid down in the sea, has formed important rock-masses in nearly all the recorded ages of the earth's history. The exact character of the rock formed in this fashion will be governed by various circumstances, such as the fineness and abundance of the material, whether it is showered into quiet waters or along a wave-beaten coast, whether and in what proportion it is mingled with sand or mud. When the volcanic ash preponderates, a tuff is formed, very much like those which accumulate on land, but more regularly stratified.

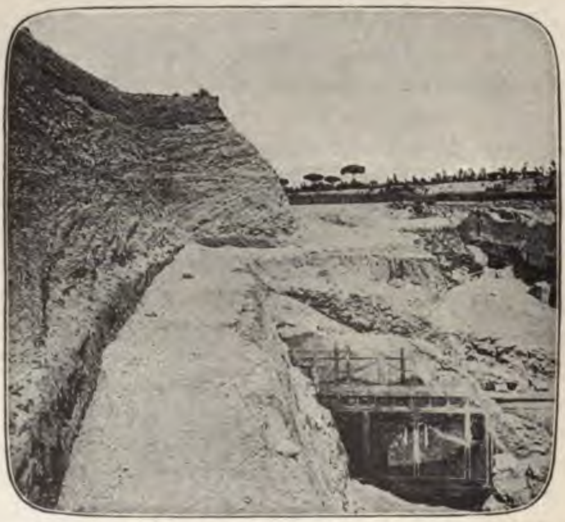

FIG. 16. — Pompeii, showing depth of volcanic accumulations. (Photograph by McAllister.)

The fragmental volcanic products, whether coarse or fine, retain their characteristic texture and appearance, so as to be readily recognizable, though perhaps only with the microscope. The great bulk of these materials consists of lava shattered by the steam explosions and quickly chilled. The coarser fragments display the frothy and vesicular nature of scoriæ, while the finer particles are glassy or crystalline. Mere comminution of the mass does not change its essential texture.

It will be readily imagined that lavas do not contain fossils. Though the flows often overwhelm living beings, the intense heat at once destroys them, leaving not a trace behind. In tuffs, on the other hand, fossils, especially those of plants, are frequently well preserved, and tuffs formed under water have fossils as abundantly as any other aqueous rocks.

FIG. 17.—Mauna Loa, seen from a distance of 40 miles. (Photograph by Libbey.)

(3) *The Gaseous Products* are important as agents of the eruptions, in promoting the crystallizing of the lavas, and in altering the rocks with which they come in contact. The most abundant is steam. Carbon dioxide is common, especially when the action is failing, and often continues after all other signs of activity have died out. Sulphurous acid (SO_2) is very characteristic and is the source of many other compounds. Sulphuretted hydrogen (H_2S) is a common volcanic gas, as is also hydrochloric acid (HCl). Several solids are vapourized, such as the chlorides of ammonium, iron, calcium, etc., but these are of little significance.

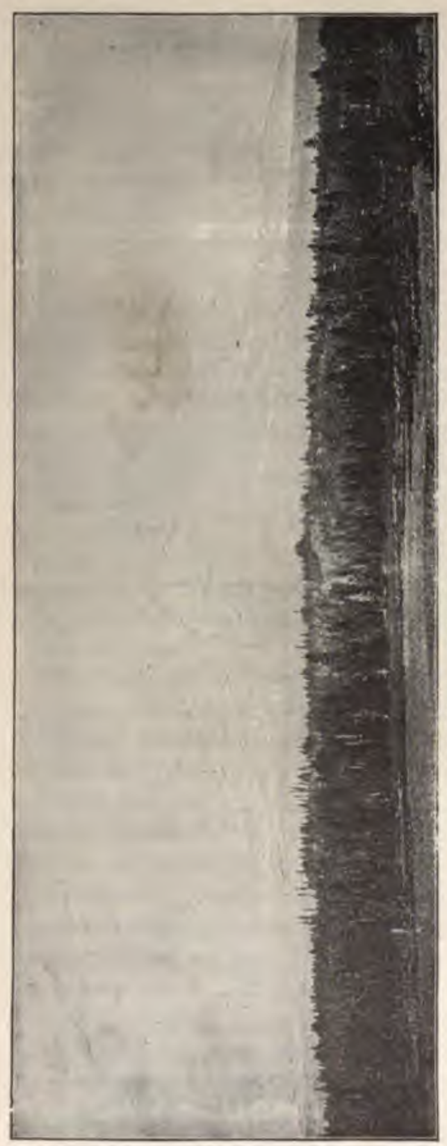

FIG. 18. — Mt. Shasta, California. (U. S. 40th Parallel Survey.)

Volcanic Cones are built up by the material which the volcanoes eject, and vary in shape according to the character of those materials and to the violence of the eruptions. Those vents which yield only lavas build up cones of solid rock, the steepness of which corresponds to the degree of fluidity of the flows. The remarkably liquid lavas of the Sandwich Islands have formed cones of exceedingly gentle slope, 3° to 10° (see Fig. 17, the cone of Mauna Loa). Very stiff lavas which consolidate rapidly form very steep-sided cones. The cones which are constructed principally out of fragmental materials are steep (30°); the more so, the coarser the fragments which compose them, and often beautifully symmetrical, as in the noble mountains of our Pacific States, such as Mt. Shasta, Mt. Hood, and Mt. Rainier. Most cones are built up of scoriæ, ashes, and lava flows, while the fissures that radiate from the crater are filled by dikes, greatly strengthening the mountain, as in the case of Vesuvius. The latter is noted for its double head, Monte Somma being part of the old cone which was mostly blown away in the eruption of 79 A.D.

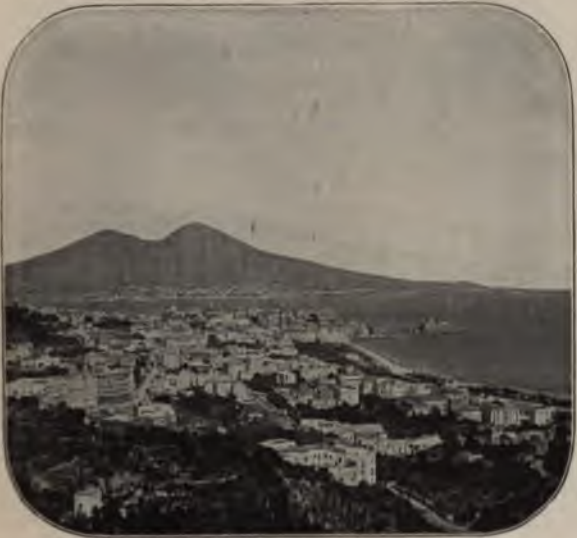

FIG. 19. — Vesuvius and Monte Somma.

Volcanoes, like other mountains, are subject to the destructive activity of the atmosphere, of rivers and of the sea, and, when eruptions have ceased, this destruction may go on with great rapidity, especially in the case of cones made up of loose materials. Very ancient cones can seldom be found, for this reason, and often the lava-filled pipe is the only record left of an ancient volcano.

Submarine Volcanoes have been actually observed in eruption in several instances, but there can be little doubt that by far the larger number have escaped detection. Not a few volcanic islands in various parts of the world have reared themselves above the sea within historic times. In fact, all volcanic islands are merely submarine volcanoes, or groups of them, which have built their cones above sea-level. If the cones are of fragmental products, the islands are but temporary, because when the activity ceases, the waves cut them down into reefs and shoals. The lava cones persist for long periods.

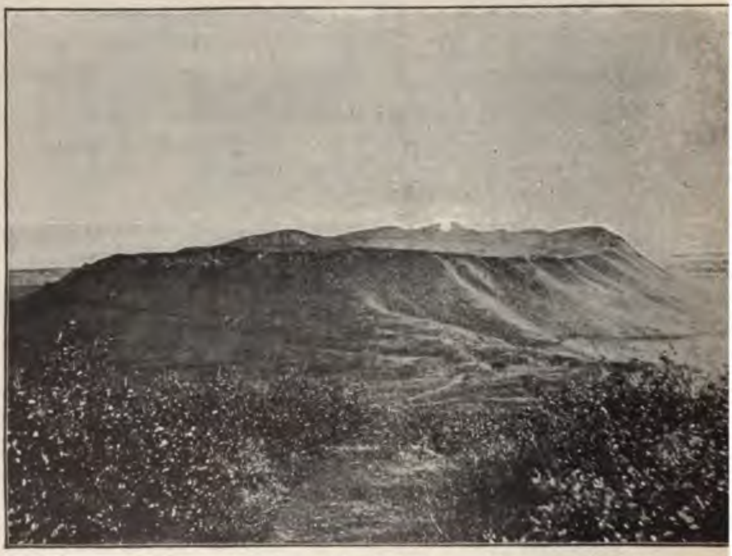

FIG. 20. — Truncated tuff cone, island of Oahu. (Photograph by Libbey.)

Fissure Eruptions. — There is much reason to believe that the mode of volcanic eruption from a single vent, described in the foregoing pages, is not the only method by which molten lava may reach the surface. It would seem that in past times lava has welled up through great fissures and overflowed immense areas in successive floods. As an example of this may be mentioned the vast fields of lava which occur in the northwestern United States, covering more than 100,000 square miles to the depth of several hundred feet. The largest connected area of this field extends along the Snake River in Idaho, southwest from the Yellowstone

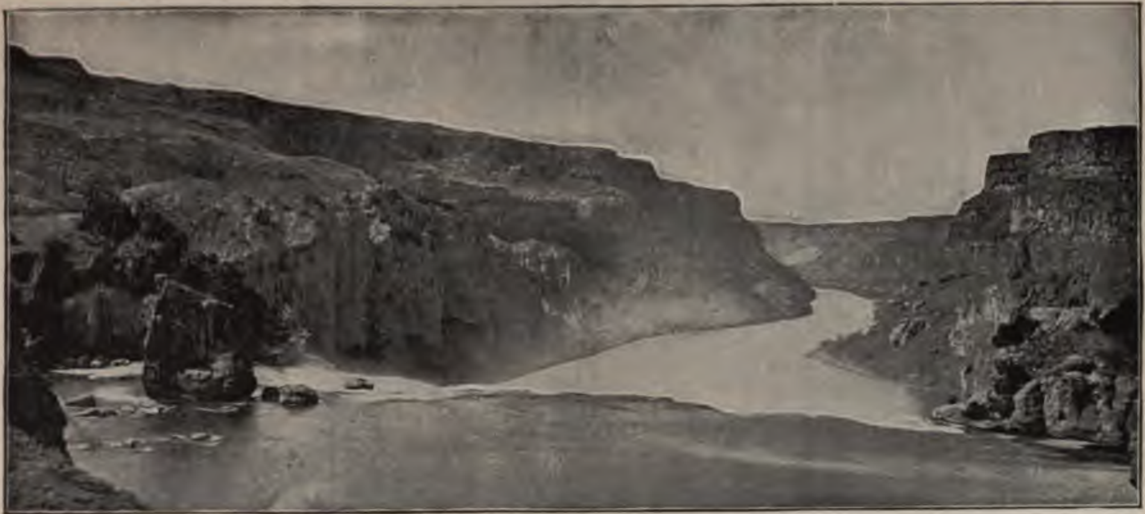

FIG. 21.—Falls of the Snake River. The gorge is cut through the great lava field of Idaho, and shows the successive flows. (U. S. 40th Parallel Survey.)

Park. Even more extensive are the lava plains of the Deccan in India, and much smaller, but still impressive, fields occur in Ireland and Scotland.

The Causes of Volcanic Activity. — Many theories have been advanced to explain the causes of volcanic activity, but none are satisfactory. In an elementary work, like the present, no adequate discussion of this most difficult problem can be given, but merely a brief sketch of some of the ways in which its solution has been attempted.

The problem is to account (1) for the intense heat of the ejected materials, (2) for the presence of the steam, (3) for the ascensive force of the lava, and (4) for the intermittency of the action, and the past and present distribution of the vents.

(1) The high temperature has been accounted for in two principal ways. By some it is supposed that it is due to the original heat of the earth, not yet lost by radiation. Of those who accept this opinion, some believe that larger or smaller portions of the earth's interior have never solidified and that these form the reservoirs of lava which supply the volcanic vents. Others again assume that the interior of the globe is exceedingly hot, but solidified by pressure; when, by fracturing or folding of the overlying rocks, this pressure is partially relieved, the highly heated masses become liquefied along that line of reduced pressure.

In the second class of hypotheses on this subject of temperature, it is supposed that the proper heat of the earth's interior is no longer sufficient to produce fusion, and that it must be supplemented from some other source. Many are the attempts to determine where this additional source of heat supply is to be found. One of the most celebrated of these attempts (Mallet) seeks the additional heat in the friction produced by the folding and crushing of rocks deep within the crust of the earth, due to the shrinkage of the earth as it cools. Others have sought to show that the heat is generated chemically, by the oxidizing effect of descending waters upon the unoxidized interior of the globe, or by the combustion of hydrogen gas.

Similar divergences of opinion obtain with regard to the nature and origin of the lavas ejected by volcanoes. The view most commonly held is that they are, for the most part, the original, unaltered material of the globe, whether this has always remained fluid, or has been remelted by release of pressure, or otherwise. According to another opinion, volcanic products are formed from the fusion of sedimentary material which was laid down under water, but has been deeply buried within the crust of the earth by subsidence. A third view recognizes both sources of supply.

(2) The problem as to the origin of the steam which plays so important a part in volcanic eruptions, is likewise very differently solved by different investigators. One opinion is that the steam, like the lava itself, is primordial and was absorbed from the atmosphere (which then contained all the waters of the sea) when the surface of the globe was still molten. Melted substances will, it is known, absorb many times their own volume of steam and gases, when in contact with them under pressure. From this it is inferred that the lava has contained the steam ever since the first cooling of the surface crust. A second opinion derives the water from the surface of the earth, supposing that it descends partly through fissures and partly through the pores of the overlying rocks by capillarity. The nearness of volcanoes to the sea is looked upon as favouring this view. Others, again, employ both methods of explanation, regarding the ordinary steam which impregnates all lavas as primordial, but believing that the violently explosive eruptions are caused by the sudden access of large bodies of water to the lava masses.

(3) The causes of the ascensive force of the lava column are likewise very differently explained by various writers. Some find an all-sufficient cause in the steam pressure, while others maintain that some other force must be at work and find this in the unequal contraction of the earth, and consequent pressure upon the molten or plastic layer beneath. It has been calculated that a radial contraction of one millimetre "would suffice to supply matter for five hundred of the greatest known volcanic eruptions" (Prestwich).

(4) The intermittency of volcanoes and their mode of distribution add to the difficulty of the whole subject, but any complete theory must explain them. The views which bring volcanic action into relation with the mechanical changes in the crust, are those which seem most consonant with the known facts of the past and present distribution of the vents.

Here, for lack of space, we must leave the subject. Enough has been said to show how far we still are from understanding the mystery of volcanoes.

CHAPTER III

EARTHQUAKES—CHANGES OF LEVEL

An earthquake consists of a series of elastic waves, similar in principle to sound waves, propagated through the crust of the earth and due to some disturbance in its interior. The number and frequency of earthquakes are exceedingly great, so much so, that the crust of the earth is in a state of constant disturbance at one or more points. Besides the trembling and shocks that may be plainly felt, minute tremors, which can be detected only by the aid of very delicate instruments, are in continual progress, even in countries rarely visited by sensible shocks. Slight shocks and movements generally pass unnoticed, but when pains are taken to collect them, it is surprising to find how numerous they are. These facts show that the crust of the earth is not the stable, rigid structure which our ordinary experience would lead us to consider it.

The Distribution of Earthquakes is very similar indeed to that of volcanoes, and volcanic regions are preëminently those in which the most frequent and violent earthquakes occur. They may manifest themselves at any part of the earth's surface, but they increase notably both in frequency and violence as the volcanic areas are approached. The great earthquakes which shook the Mississippi valley in 1811–12, are among the very few instances of violent and long-continued shocks in a region far from any volcano. Yet, even these would appear to have had some connection with the volcano of St. Vincent in the West Indies, and ceased when that vent became active.

The earthquake, or *seismic*,[1] bands thus follow the coast-lines and mountain chains, and coincide with the volcanic bands, but are much wider than the latter, earthquakes being propagated over wider areas from the seat of disturbance than the effects of volcanoes, except in the case of the unusually terrible explosions. In one respect, the earthquake bands deviate quite markedly from the volcanic; namely, in the presence of a seismic zone which encircles the whole earth. This belt includes the Mediterranean lands, the Azores, the West Indies and Central America, the Sandwich Islands, Japan, China, India, Persia, and Asia Minor. By some authorities this is regarded as the main seismic band, especially liable to disturbance, from which the others are but branches. Volcanoes occur in many parts of the belt, but they form no such continuous band around the earth.

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[1] Greek *seismos*, earthquake.

The Phenomena of Earthquakes are of very great significance from the standpoint of human interests, because of the appalling destruction and loss of life which they often cause. Fearful results may be caused by a heaving of the ground in which there is little actual displacement. The phenomena vary considerably, according to the position of the place observed with reference to the *focus*, or seat of disturbance, the violence of the shock, and the character of the rocks through which the vibrations are transmitted. Were the focus a point, and the rocks uniformly elastic and homogeneous, the earthquake waves would be spherical, and their outcroppings at the surface (which produce the sensible shocks) would be circular. But none of these conditions exist, and so the waves are more or less irregular, and owing to differences in the rocks, reflection and interference of the waves, and the like, the result often seems most anomalous and capricious. This, however, is not of sufficient importance for our purpose to require description.

When the shock occurs beneath the bed of the sea, the phenomena are complicated by disturbances in the water. Of these, the most important is the *great sea wave* (erroneously called tidal wave), which, though not strikingly displayed in the open sea, in shallow water piles up into enormous breakers and rushes upon the coast, often doing far more damage than the earth waves themselves.

One important result of the modern careful investigation of earthquakes is to show that they are comparatively superficial phenomena, which arise within and not below the crust of the earth. The focus is usually situated at depths of eight or ten miles, while depths of twenty-five to thirty miles are uncommon.

The Effects of Earthquakes are geologically less important than is usually supposed, and some of them which are commonly called effects of earthquakes, are rather collateral results of the forces which produced the earthquake. The heaving and wave-like rolling of the ground, when violent, bring about great landslips in mountain regions, and shake down enormous masses of earth and rock from the cliffs and slopes, into the valleys beneath. Destruction of this character on a gigantic scale was a marked feature of the great earthquakes which shook northwestern Greece in 1870. These falling masses may temporarily or permanently block up the mouth of a mountain valley, and by damming back the stream which flows in the valley, convert it into a lake. The course of rivers is not unfrequently altered by earthquakes, a ridge being thrown up athwart the stream. Along the west coast of South America are found many deserted stream channels, the streams having evidently been diverted by the upheaval of ridges across their courses. In a narrow valley such a ridge will act as a dam and form a lake, but on a plain the stream will be diverted to a new course.

A very common accompaniment of violent earthquakes is the opening of cracks and fissures in the ground; these may close up again after the shock has passed, but they often remain open as yawning chasms. The two sides of such a fissure may remain at the same relative level as before, or one side may be raised up or dropped down, producing a dislocation or *fault*. The earthquake which originated in Owen's Valley, California, in 1872, and was one of the most violent recorded within the United States, was accompanied by a series of faults, running along the base of the Sierra Nevada, and having a maximum displacement of twenty feet. In May, 1887, an earthquake in Arizona and Sonora (Mexico) was accompanied by a fault, which has been traced for thirty-five miles, and has an average displacement of seven feet. Similar phenomena have been recorded from many parts of the world.

The Causes of Earthquakes are better understood than those of volcanoes, though much still remains which is difficult of explanation. All earthquakes are not due to the same causes, for any operation which will produce a blow or jar in the earth's interior sufficiently strong to be propagated as a series of elastic waves to the surface, will cause an earthquake. The most frequent of such sources of disturbance are of two kinds.

(1) In volcanic regions the explosions of steam are very often the cause of earthquakes. This explains the association of earthquakes and volcanoes in the same region, and also the fact that a great volcanic eruption is usually heralded by earthquakes, which increase in violence up to the time of the outbreak, and then cease. Though more than two thousand miles distant, the eruption of St. Vincent relieved the Mississippi valley earthquakes. It must not be supposed, however, that all the earthquakes which occur in volcanic areas can be brought into relation with eruptions, for many of them cannot, as in the case of the countries around the Mediterranean and of Japan.

(2) A second and probably more important and widespread cause of earthquakes is the sudden yielding of the earth's crust to the strains which are set up within it. The contraction of the earth must establish cumulative stresses in the crust, which, if yielded to gradually, would not cause a jar, but when resisted, increase until the strength of the rocks is overcome, and they give way with a sudden shock, which produces an earthquake. The association of volcanoes and earthquakes in the same regions is thus not altogether, probably not even principally, a relation of cause and effect, but is rather due to the fact that both are connected with lines of fracture and weakness in the earth's crust. In non-volcanic regions nearly all the earthquakes may be traced to such lines of fracture, wherever the data have been collected for an accurate determination of the foci.

CHANGES OF LEVEL

As was mentioned in the preceding section, permanent changes of level frequently accompany earthquakes; but these are paroxysmal, and appear to be nearly always the result of dislocation or faulting. By change of level, in the general sense, is meant the gradual, steady upheaval or subsidence of land, with reference to the sea, over considerable areas. Such movements are very slow, and hence are apt to escape observation; so long are the periods of time involved, that there is much dispute as to the facts, and still more as to the interpretation of them.

The method by which any change in the relative position of the land may be detected, is by comparison with the sea, and hence such observations, so far as they refer to changes now in progress, are confined to the coast. Obviously, the result would be the same if the change were in the sea, and it is somewhat doubtful which is to be regarded as the seat of a given oscillation. Until quite lately it was always taken for granted that the sea-level is constant, and that the surface of the oceans is everywhere that of a true spheroid, concentric with the figure of the earth. Recent exact investigations have, however, thrown much doubt upon this assumption, and indicated that the sea-level may be markedly different at different places. By this is not meant the temporary change due to the heaping up of the waters by the wind, or by unusual tides, but a real and permanent difference of average level. There is reason to believe that the attraction of the continents, of great mountain ranges and lofty plateaus near the coast, raises the water to a higher level than in the open sea, or along flat, low-lying shores.

These local differences greatly complicate the problem of determining just what processes are at work in the apparent elevation and depression of land. For this reason some geologists have proposed to avoid the terms *elevation* and *depression*, and to substitute for them "positive and negative displacements of the coast-line," which are non-committal with reference to the real character of the movement. For the sake of convenience, it will be best to retain the older and more current terms, without insisting that in all cases the changes lie in the land rather than in the sea.

Another process which must be carefully distinguished from the true changes of level is the alteration of the coast-line due to the washing away of land by the sea, causing the latter to advance, or, on the other hand, to the silting up of shallow water by the deposition of sand or mud, which makes the land advance at the expense of the sea.

The evidences of elevation along any coast-line may be more easily made out than those of depression, because when land comes up out of the sea, the traces of marine action upon its surface are always present in one form or another. When, on the contrary, land goes down beneath the sea or the sea rises over the land, the old land surface is speedily changed and buried out of sight.

Evidences of Elevation. — Along coasts which have been inhabited for many centuries by civilized man, ancient structures, like quays and bridges, which were built in the water may now be found high above it. Such changes have been noted in the lands which adjoin the Mediterranean, especially in southern Italy and the island of Crete. The temple of Jupiter Serapis at Puzzuoli, near Naples, is a classic example of this. In this building three marble columns are still standing, and on each of them is a belt, about ten feet above the ground and nine feet wide, honey-combed by the boring mollusc, *Lithodomus*, which still lives in the neighbouring bay. Evidently the temple was first submerged, and when under water the columns were attacked by the mollusc, and afterwards it was upheaved, but is now sinking once more.

Rocks and cliffs long exposed to the action of the surf are worn and marked in a characteristic fashion, and when found far above where the surf can now reach them, are evidences of upheaval at that point. Such well-defined sea-marks high above sea-level are common in the high latitudes of the northern hemisphere, and the change is still in progress in many places. The Scandinavian peninsula shows slow changes of level, though not everywhere the same ; south of Stockholm there is a slight subsidence, north of that point there is a rise, which increases northward, and at the North Cape is believed to average five or six feet per century. These results have been much questioned, but after a renewed examination of the dated tide marks cut on the cliffs at various periods in the last century and early in the present one, the Swedish geologists have strongly reaffirmed them.

Interesting examples of recent elevation are believed to occur in the neighbourhood of Washington, D.C. In colonial times Bladensburg and Dumfries could be reached by sea-going ships, but now they are decidedly above tide-level. The change is generally supposed to be due to a silting up of the creeks, but this appears not to be the case, for there is little alluvium resting upon the bed-rock of the channels.

In many parts of the world are found beaches, raised far above the sea-level, and these point to an elevation of the land. Such raised beaches occur in Scandinavia, Great Britain, the West Indies, the Red Sea, the southern end of South America, and elsewhere. In these beaches are often found the remains of marine animals, shells, corals, barnacles, and the like, and wherever such remains occur in undisturbed position, they prove conclusively either that the land has been upheaved or that the sea has gone down at that point. The form and character of the coast-line itself may be evidence of comparatively recent elevation, as will be explained in Part III.

Evidences of Depression. — Ancient buildings, which were evidently constructed on land, but now are below the sea, show a subsidence at the point where they occur. These are found in several of the Mediterranean lands and on the west coast of Greenland. In the latter country the change is relatively rapid, and has attracted the attention of the inhabitants.

Buried forests found below the level of the sea indicate subsidence. Such forests occur in the Mississippi delta and at many points on the coast of the middle and southern Atlantic States, notably in New Jersey, where the coast is sinking at a rate estimated as two feet per century.

Submerged river-channels are likewise evidences of depression, because a river which flows into the sea cannot excavate its bed below the level of the sea-bottom at its mouth. Many such instances are known, but it will suffice to mention the case of the

Hudson, whose ancient channel has been traced by means of soundings for one hundred miles outside of Sandy Hook.

A great thickness of shallow-water deposits is another obvious proof of depression; for if the sea-bottom did not sink, the water would soon be filled up where it is shallow, and the coast-line advanced. When we come to study the materials which are now accumulating on the ocean floor, we shall learn how the depth of water may be inferred from the character of the deposits. At present it is only necessary to say that, from the Hudson River southward, the Atlantic coastal plain is covered by a great thickness of shallow-water beds, as revealed by the numerous artesian wells which have been driven through it. A coast may also betray recent subsidence by its form, but an account of this must be deferred till we reach Part III.

The Causes of Elevation and Depression. — Perplexing and obscure as we have found the causes of the other subterranean agencies to be, those which control the changes of level are far more so, and no theory of their action yet propounded is at all adequate or satisfactory. Perhaps the most generally accepted view is that which brings them into relation with the secular contraction of the earth, due to the slow shrinkage of the heated interior, as it gradually cools, together with the flow of plastic subcrustal material away from the lines of greatest pressure. This theory is, however, very vague, and cannot be crucially tested.

Another kind of movement of the crust of the earth is believed to be that which follows upon changes of the load which any given area has to carry. We shall see in later chapters that the rain, wind, and rivers are continually cutting down the land surface and carrying the materials thus obtained to the sea, where they accumulate in great sheets. By some authorities it is believed that the crust of the earth is in so exact a state of equilibrium, that any area upon which a load of sediment is deposited will sink, while one whence material is removed will rise because its load is lightened. This kind of adjustment is called *isostasy*, and its effect is to preserve the inequalities of the earth's surface as they already exist, while the general movements of elevation and depression must be quite independent of isostatic adjustment, because they increase or diminish those inequalities.

The most recent investigations are unfavourable to this view of isostasy, and go to show that the crust is not so sensitive to changes of load. While the major inequalities, the great continental platforms and oceanic depressions, are not improbably due to differences of density in the crust, minor inequalities, like hills and mountains, are apparently sustained by the rigidity of the crust.

Summary.—The study of the subterranean, or igneous, agencies has proved to be very unsatisfactory in the way of explaining the phenomena and referring them to the operation of understood physical agents, because so little is really known and so much remains to be discovered. Nevertheless, we have learned much that is of great importance in geological reasoning. We have seen that the earth contains within itself a great store of energy, and that its interior, in whatever physical state that may be, is highly heated, and possesses great quantities of material which is either actually or potentially molten, and is permeated with superheated steam and other gases. This molten material is often forced upward, and is either poured out at the surface, or fills up fissures and cavities in the rocks, or pushes its way between them. Cooling under various circumstances, the molten masses consolidate into a great variety of characteristic rocks, frothy, glassy, or crystalline. Explosive discharges of steam blow the melted rock into fragments of all grades of fineness, and these fragments likewise accumulate either on the land or under water, and form rocks, the nature and origin of which may be readily recognized.

We have further seen that the operation of these subterranean forces produces shocks and jars in the interior, which are propagated to the surface as earthquakes, and there bring about permanent changes, associated with the fissuring and dislocation of the rocks, landslips, alteration in the course of rivers, formation of lakes, and the like. The frequency of earthquakes, their wide geographical range, and the constant tremor of the ground detected by delicate instruments, led us to infer that the crust of the earth is decidedly unstable.

This conclusion we found strengthened by the oscillations of level between land and sea, which, though extremely slow, are seen to be still in progress. Historical geology will show us that these changes of level have, in the course of ages, been effected on the grandest scale. All the great continents are composed of rocks, which, for the most part, were laid down in the sea and still contain the fossils of marine animals, and this shows that these continents have all been under the sea. Not that all the continents, or even that all parts of any one continent, were submerged at the same time, but now one part and now another was overflowed and again emerged, until all have been covered in their turn.

In brief, the principal geological functions of the subterranean agencies are two: (1) they bring up from below and form at the surface, and at all depths beneath it, certain characteristic kinds of rocks; and (2) they tend to increase the inequalities of the earth's surface, and thus to counteract the agencies which are cutting down the land and steadily tending to reduce it to the level of the sea.

SECTION II

SURFACE AGENCIES

THE surface or superficial agents are those which act upon or very near the surface of the ground and all of which are manifestations of solar energy. Their work may all be summed up in two categories, the *destruction* and *reconstruction of rock*. These two processes are complementary; for since matter cannot be destroyed, but can have only its position and its physical and chemical relations changed, it is obvious that what is removed in one place must be laid down in another. Thus, neither of these processes can go on without the other, and reconstruction always implies antecedent destruction to furnish the materials. Everywhere we find ceaseless cycles of change in progress, new combinations of material being continually formed and older rocks steadily worked over into newer. It is this circulation of matter upon and within the crust of the earth that we have already compared to the physiological changes in the body of a living organism.

It is important to remember that the processes of rock destruction, which are grouped together under the general name of *denudation* or *erosion*, are confined almost entirely to the land surfaces, while those of reconstruction take place principally beneath bodies of water. Some work of reconstruction is also accomplished on the land, but this is of very minor importance.

Since destruction necessarily precedes reconstruction, the consideration of these processes will naturally begin with those of destruction or denudation. The destructive agencies are: (1) the atmosphere, (2) running water, (3) ice, (4) lakes, (5) the sea, (6) plants and animals.

CHAPTER IV

DESTRUCTIVE PROCESSES — THE ATMOSPHERE

THE atmospheric agencies are by far the most important of the destructive or denuding agents, because no part of the land surface is altogether exempt from their activity. Their work is described by the general term *weathering*, and is shown at once by the different appearance of freshly quarried stone from that which has been long exposed in the face of a cliff, or even in ancient buildings. While such agents as rivers and the sea do work that is much more apparent and striking than that of the atmosphere, yet they are much more locally confined, and even in their operations the atmosphere renders important aid. Though no part of the land surface is entirely free from the destructive activity of the atmosphere, the rapidity and intensity of this activity vary much in different places. There are, in the first place, the great differences of climate to be considered, differences in the amount and distribution of the rainfall, of temperature, and of the winds. In the second place, the resistance offered by the various kinds of rocks to the disintegrating processes differs very greatly, in accordance with the differences of hardness and chemical composition. Again, the presence or absence of a covering of protective vegetation has an important influence upon the amount and character of the destruction effected.

The outcome of all these varying factors is to produce very irregular land surfaces. While the tendency of the atmospheric agencies is gradually to wear down the land to the level of the sea, yet in that process some parts are cut away much more rapidly than others; and hence the *first effect* of denudation is an increasingly irregular surface. The overlying screen of soil conceals many of these irregularities, especially the minor ones; and were that screen removed, the ruggedness of the underlying rocks would be seen to be much more decided than now appears. So long as the land has these irregularities, it is said to possess *relief;* and when it is all planed down to a flat or gently sloping surface but slightly raised above the sea, it is said to have reached the *base-level of erosion*, or to be *base-levelled.*

The atmospheric agencies may be conveniently divided into (1) rain, (2) frost, (3) changes of temperature, (4) wind.

1. Rain

Perfectly pure water, containing neither gases nor solids in solution, would have very little disintegrating effect upon most rocks, but pure water does not occur in nature. The raindrops, generated by the condensation of the watery vapour of the atmosphere, absorb certain gases, which add very materially to the dissolving powers of the water. Of these gases the most important are oxygen (O) and carbon dioxide (CO_2), and all rain-water contains them.

As rain-water percolates through the soil, it acquires additional destructive powers by dissolving the acids formed by the decomposition of vegetable matter, which are grouped together under the name of *humous acids.* These acids have the power of decomposing or dissolving many minerals which resist the action of ordinary rain, and thus it is that many rocks which, when exposed to the action of the atmosphere only, waste very slowly, disintegrate with comparative rapidity underground. One of the first and simplest effects of atmospheric moisture consists in the oxidation and hydration of the minerals exposed to it. Hydration, or the taking up of water into chemical union, is an important agency of decay. It is accompanied by an increase of bulk, and hence in the lower layers of a rock-mass greatly augments the pressure. In the District of Columbia "granite rocks have been shown to have become disintegrated for a depth of many feet, with loss of but some 13.46 per cent of their chemical constituents. . . . Natural joint blocks brought up from shafts were, on casual inspection, sound and fresh. It was noted, however, that on exposure to the atmosphere, such not infrequently shortly fell away to the condition of sand" (Merrill).

Nearly all rocks contain materials which are more or less soluble or destructible in rain-water, though usually these soluble materials make up but a small proportion of the whole. When they are removed, the rock crumbles into a friable mass which, on complete disintegration, forms soil. Frozen soil, though with only a small quantity of ice in it, is as hard as many rocks, the ice acting as a cement and firmly binding the granules together. When the cementing ice loses its coherence by melting, the rock-like mass becomes friable. This illustrates the effect of removing a small quantity of soluble material from a hard rock. Except vegetable moulds, all soils are derived from the disintegration of rocks.

The materials out of which rocks are made vary so much that the chemical processes which destroy them must be correspondingly different. Our survey of the disintegrating agencies will naturally begin with those rocks which have once been melted, or the *igneous rocks*, because, as we believe, the first solid crust of the globe was formed of such rocks, and from them started the cycles of change and circulation of matter which are still going on.

The great majority of the igneous rocks are made up of crystals of some variety of felspar (see p. 16) associated with other minerals, such as hornblende (p. 20), mica (p. 18), quartz (p. 15), etc. As an example, we may take granite, which is composed of orthoclase felspar, quartz (SiO_2), and mica or hornblende, both of which are complex silicates of iron, lime, etc. Rain-water falling upon an exposed mass of granite, or reaching it by underground percolation, slowly decomposes the orthoclase, either removing the potash in the form of a soluble silicate, or converting the silicate into carbonate. The silicate of alumina, which is left behind, absorbs water and forms clay or *kaolin* (Al_2O_3, $2\ SiO_2$, $2\ H_2O$). The quartz is unaffected by the rain-water, being insoluble and a very simple and stable compound, which is not decomposed into simpler substances by ordinary natural agents. The mica is very slowly disintegrated.

The result of the decomposition of granite, then, is the formation of a mass of clay, through which are disseminated the unchanged grains of quartz and mica. In the other igneous rocks the mode of disintegration is essentially the same: the complex silicates are decomposed into simpler compounds, clay being the principal derivative of the felspars, while the quartz, if present, is broken up into fragments and forms sand. Even when an igneous rock is yet firm and hard and, examined by the naked eye, appears to be quite unchanged, the microscope often reveals important chemical changes, which are the first steps of decay.

The circulation of the material of rocks is continuous, and rocks which are themselves composed of substances derived from the decay of older rocks are attacked in their turn and yield material for new formations. These derivative rocks, such as sandstones, slates, and limestones, are affected in characteristic ways by the rain.

Sandstones are composed of grains of sand (quartz, SiO_2) cemented together; the cementing substance may be silica itself, some compound of iron, such as Fe_2O_3, or carbonate of lime ($CaCO_3$), and the dissolving away of the cement causes the rock to crumble into sand. In a sandstone with siliceous cement the action is excessively slow, atmospheric waters having very little effect upon silica, but underground the humous acids are believed to dissolve it slightly. Ferric oxide (Fe_2O_3) is likewise unchanged by rain-water, but beneath the soil decomposing organic substances deoxidize it into FeO, which, taking up CO_2, forms the soluble carbonate of iron ($FeCO_3$). The uppermost layers of red sandstone are often thus completely disintegrated into loose sand, bleached by the removal of the iron which gave it its colour. Carbonate of lime is very soluble in water containing carbon dioxide, as all rain-water does, and in sandstones with calcareous cement, disintegration is rapid. In sandstones and slates it is the cementing substance which is removed, leaving the grains of sand or particles of clay unchanged, and the limestones are simply dissolved. This is because the materials of these rocks were, for the most part, originally derived from the decomposition of the igneous rocks, and the minerals which compose them are already of a very simple and stable character.

The sandstones are largely employed for building materials, and their value and permanence for such purposes depend principally upon the character of the cementing substances in them. For this reason, the siliceous and ferruginous sandstones are the most durable, those with calcareous cements usually yielding with comparative rapidity to the attacks of the weather.

Slates and shales, by removal of their soluble constituents, crumble down into clay.

Limestones are among the few rocks which are chiefly or entirely made up of soluble material, the carbonate of lime ($CaCO_3$). This is attacked by the rain-water, dissolved and carried away in solution, while the insoluble impurities contained in the rock remain to form soil. The proportion of such impurities varies greatly in different limestones, and hence the residual soil will vary, but it is generally a clay, since that is much the commonest of the impurities in limestone. Sand also occurs in limestones, either with or without clay. When the sand forms a coherent mass, out of which the calcareous material has been dissolved, it is called *rotten-stone.*

The gradual formation of soil by the disintegration of rock may be easily observed in excavations, even shallow ones, such as cellars, wells, railroad cuttings, and the like. At the surface is the true soil, which is usually dark coloured, due partly to the admixture of vegetable mould, partly to the complete oxidation and hydration of its minerals. Next follows the subsoil, which, owing to the absence of vegetable matter and the less complete oxidation and hydration, is of a lighter colour. The subsoil is frequently divided into distinct layers, and often contains unaltered masses of the parent rock, which have resisted decomposition, while the surrounding parts have become entirely disintegrated. By imperceptible gradations the subsoil shades into what looks like unaltered rock, but is friable and crumbles in the fingers; this is *rotten rock.* From this to the firm, unchanged rock, the passage is equally gradual.

In the northern portions of the United States the soil is, in most localities, of only moderate depths, because at a late period (geologically speaking) this region was covered with a great ice-sheet, which swept away much of the accumulations of ancient rock-decay. In the parts of the country where the ice-sheet did not come, the soil is much deeper, and in tropical lands it attains remarkable depths. In our Southern States the felspathic rocks are often found thoroughly disintegrated to depths of 50 or 100 feet, while in Brazil the soil is often 200 to 300 feet deep.

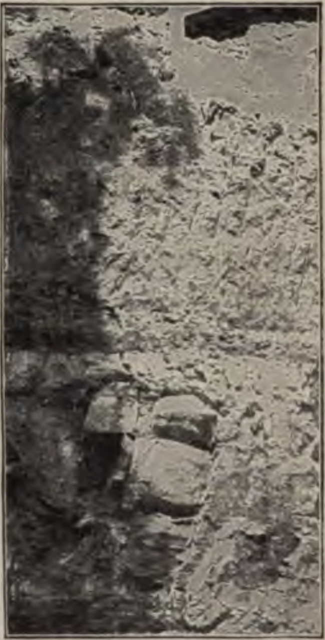

FIG. 22. — Excavation displaying the transition from rock below to soil above.

The mechanical effect of rain is less extensive, perhaps, than its chemical work of disintegration, but is very important, nevertheless. Under ordinary conditions, this mechanical work consists in the washing of soil from higher to lower levels. How considerable is the movement of soil that has thus been brought about, may be imagined when one sees, after a heavy rain, the rain-rills which run over the slopes, muddy and charged with sediments, and how turbid the streams become with the soil which the rain washes into them. Bare soil is rapidly torn up and washed away by the action of rain, but a covering of vegetation, and especially of the elastic and matted stems and roots of grasses, much retards the action.

Other things being equal, the rapidity with which the rain sweeps away the soil depends upon the steepness of the slope upon which the soil is formed; for gravity largely determines these movements. On vertical cliffs and steep hillsides it is quickly removed, and in such places it is thin or quite lacking, while in the valleys it often accumulates to great depths. Even on gentle slopes and almost level stretches the rains slowly wash it downward, and eventually into the streams which carry it to the sea. The soil is thus not stationary, but under the influence of the rains and streams is slowly but steadily travelling seaward. Disregarding the alluvial deposits made by rivers, and soils accumulated by the action of ice or wind, the soil of any district is thus a residual product, and its quantity represents the surplus of chemical disintegration over mechanical removal.

The mechanical action of rain is greatly increased by extreme violence and volume of precipitation; a single "cloud-burst" will do far more damage than the same quantity of rain falling in gentle showers. Those who know only the temperate regions can form but imperfect conceptions of the violence of tropical rains. On the southern foot-hills of the Himalayas, for example, the rainfall is exceedingly great (in some localities as much as 500 inches per annum), and almost all of it is precipitated in six months of the year; especially remarkable is the quantity which often falls in a single day. "The channel of every torrent and stream is swollen at this season, and much sandstone and other rocks are reduced to sand and gravel by the flooded streams. So great is the superficial waste, that what would otherwise be a rich and luxuriantly wooded region is converted into a wild and barren moorland" (Lyell).

The action of rain is thus by no means uniform, the results depending upon so many and such varying factors, that we may find marked differences in closely adjoining regions, and even in one and the same mass of rock. One of the most remarkable monuments of rain-erosion is exhibited by the curious districts in the far western states known as the "*bad lands*," which cover many thousands of square miles in the Dakotas, Nebraska, Wyoming, Utah, etc. The bad-land rocks are mostly rather soft sandstones and clays, with prevailingly calcareous cements, and formed in nearly horizontal beds or layers. The rainfall is light, though torrential showers sometimes occur; but the absence of vegetation is favourable to its efficiency, and the present aridity of the climate is not of very long standing, from a geological point of view. The chemical action of the rain has disintegrated the rocks by dissolving out the calcareous cement, and then the débris so formed has been mechanically washed away.

At the present time the action of the rain is very slow, because the débris which covers the sides of the cliffs and slopes is almost impervious to water, and holes left by the excavation of fossil skeletons often remain visible for many years; but where the bare rock is exposed, the disintegration often proceeds with extraordinary rapidity, and a single shower will produce notable effects. The different layers of rock resist decay differently, and even in the same bed some parts are much more durable than others. This differential weathering has resulted in that remarkable variety and grotesqueness of form, resembling the ruins of gigantic towers and castles, for which the bad-land scenery is famous. The sculpture of the rain produces this variety in ac-

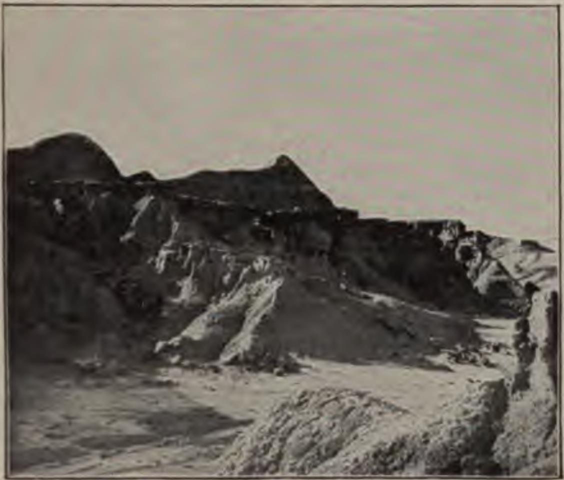

FIG. 23.—Bad lands of South Dakota. (Photograph by Williston.)

cordance with the arrangement of the more and less durable layers. When the harder beds are at the top, flat-topped tables, or *mesas*, with steep sides, are carved out; when this hard bed is removed, or was not originally present, rounded and dome-shaped hills and high, narrow, and precipitous *buttes* result, with the more durable layers cropping out on the sides as projecting ledges. Isolated hard patches, by protecting the softer beds beneath them, gradually cause the formation of pillars, as the unprotected portions are cut away, and these pillars may be observed in all stages of their formation. Monument Park, in Colorado, is especially noted for this feature. Eventually the hard cap of the pillar becomes undermined and falls, and then the shaft is speedily removed.

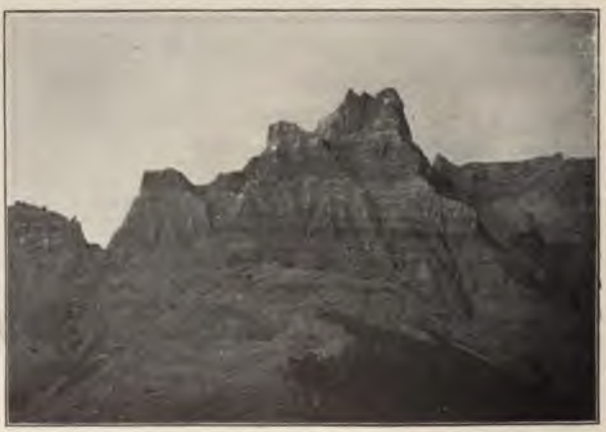

FIG. 24.—Bad-land peak, South Dakota. The horizontal stratification is very plainly marked.

2. FROST

The term *frost*, in this connection, is restricted to the freezing of water. Water is one of the comparatively few substances which expand considerably on passing from the liquid to the solid state. This expansion, which amounts to about one-eleventh of the original bulk of the water, takes place with irresistible power, bursting thick iron vessels like egg-shells.

Excepting loose, incoherent masses, like sand and gravel, no rocks are formed of continuous sheets of material, but are rather to be considered as masses of blocks, divided by the *joints*. (See pp. 48 and 200.) In addition to these visible clefts, the blocks are traversed by minute crevices, rifts, and pores, all of which openings take up and retain quantities of water, as may readily be seen by examining freshly quarried stone. When exposed to a low temperature, the water freezes and forces out the large blocks and shatters them into pieces of smaller and smaller size. The fragments thus formed are called *talus*, and great accumulations of such blocks are found at the foot of cliffs in all regions where the winters are at all severe. Talus accumulations are also formed by other agencies, as will be seen in the sequel. Alternate freezings and thawings not only break up rocks, but cause the broken fragments and soil to work their way down slopes. Each freezing

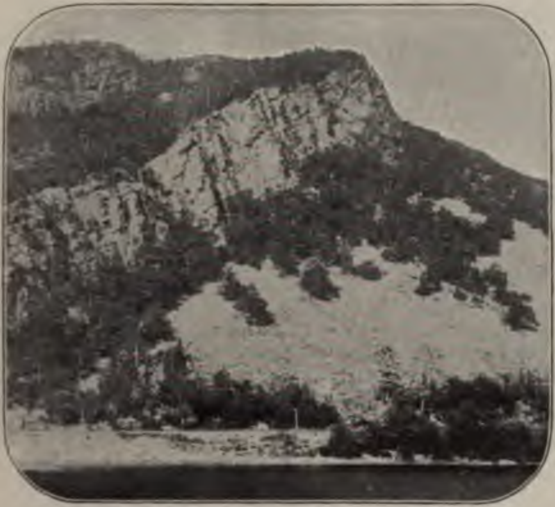

FIG. 25.—Cliff and talus slope, Delaware Water Gap, Pa.

causes the fragments to rise slightly at right angles to the inclined surface, and each thawing produces a reverse movement; hence the slow *creep* down the slope.

The action of frost is, of course, practically absent in the lowlands of the tropics, but in high mountains and in all countries which have cold winters, frost is an agent of great importance in the mechanical shattering of rocks and slow destruction of cliffs. The hardest rocks are shivered into fragments and, dislodged from their places, the fragments roll down the mountain side till they come to rest, perhaps thousands of feet below. Immense accumulations of frost-made talus are to be found in such places as the foot of the Palisades of the Hudson, the abrupt southern slope of

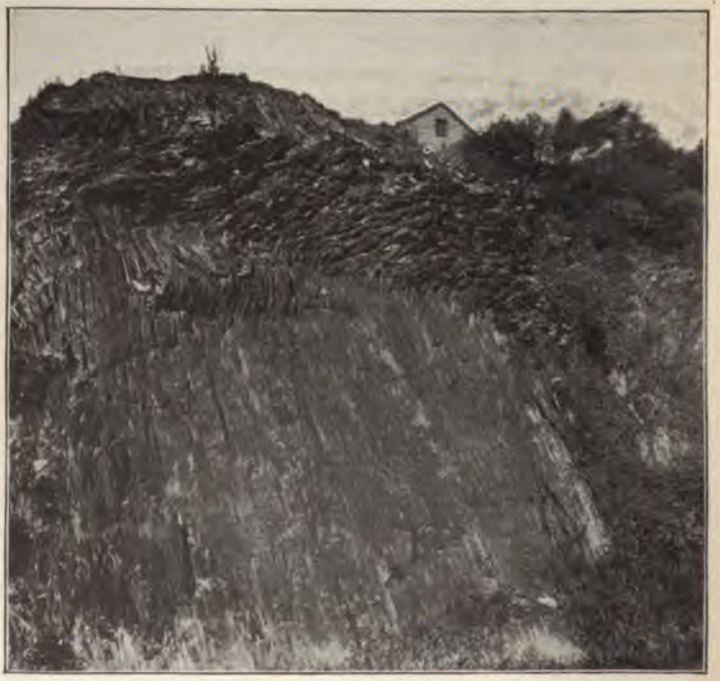

FIG. 26. — Shales "creeping" under the action of frost. (U. S. G. S.)

the Delaware Water Gap, and wherever cliffs or peaks of naked rock are exposed to severe cold. Many mountain passes are so bombarded by falling stones as to be extremely dangerous; in the Sierra Nevada of California talus slopes as much as 4000 feet high are reported, all the work of frost. At Sherman, where the Union Pacific railroad crosses the "continental divide," the ground is covered for miles with small, angular fragments of granite broken up by the frost.

In the polar regions frost is probably the most important of the disintegrating agents. In Spitzbergen Beechy found that in summer the mountain slopes absorb quantities of water, which freezes in winter with very destructive effect. "Masses of rock were, in consequence, repeatedly detached from the hills, accompanied by a loud report, and falling from a great height, were shattered to fragments at the base of the mountain, there to undergo more rapid disintegration." Similar phenomena are reported from the Aleutian Islands of Alaska.

The action of frost is, in itself, purely mechanical, no chemical change is occasioned by it, and the smallest fragments into which a block may be riven are sharp and angular, and the minerals have unaltered and shining faces. But, on the other hand, frost prepares the way for the more rapid action of rain and percolating waters. The effects of these agents are produced upon the surface of the rocks and the walls of the crevices which run through them. By breaking up the blocks, the frost greatly increases the surface and thus facilitates the work of the rain. An example will make this clear. A cube of stone, measuring one foot each way, has six sides, each of 144 square inches, and its total superficies is thus $144 \times 6 = 864$ square inches. Suppose this block to be riven by the frost into pieces of one cubic inch each; of such small cubes there will be 1728, each with six square inches of surface, giving 10,368 square inches of superficies for all the cubes. A breaking up of the cubic foot into cubic inches thus multiplies the exposed surface by 12.

Rain and frost are agents whose effects are most important in regions of moist climate and abundant rainfall, for both are forms of the activity of water. Few regions of the earth's surface are altogether rainless, but nearly all of the continents have great desert areas in which atmospheric precipitation is very light. It might seem that in such deserts the work of rock disintegration must be practically at a standstill, and that the circulation of material must be so slow as to be hardly distinguishable from complete stagnation. Even in these regions, however, the rain accomplishes something, and it is aided by other agencies which in moist climates play a much more modest rôle; these are the changes of temperature and the wind.

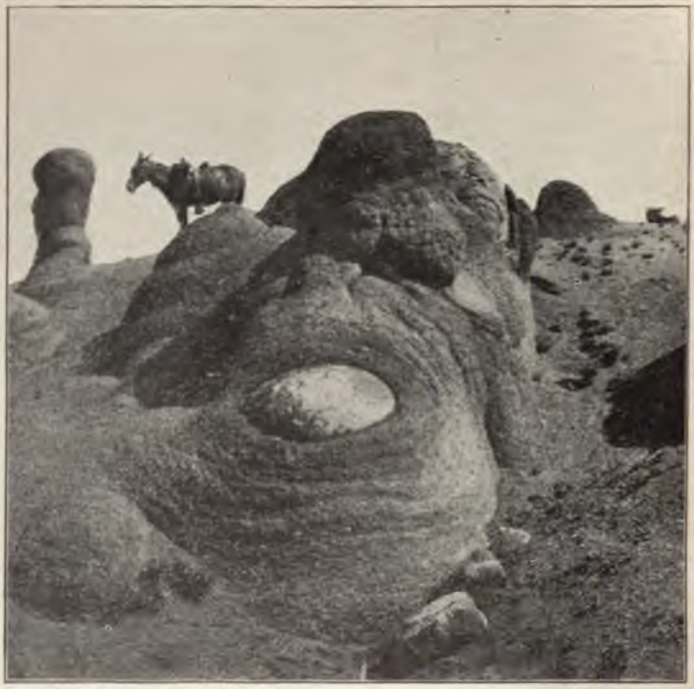

FIG. 27. — Weathered and exfoliating granite, Sierra Nevada, California. (U. S. G. S.)

3. CHANGES OF TEMPERATURE

These changes, by alternately expanding and contracting the rocks, widen the crevices and fissures which traverse them. In humid climates this agency is a very subordinate one, and acts chiefly in preparing an easier path for percolating waters, but in dry regions it becomes much more important. In the latter case, the naked rocks are, during the day, heated to a high temperature by the full blaze of the sun, and at night the rapid radiation which occurs in dry air, cools them very quickly. When radiation begins, the outer layers of the rock chill rapidly and attempt to contract upon the still heated and therefore expanded interior; thus strains are set up which the rock cannot resist, and, therefore, great pieces are split off. In this fashion talus slopes of angular blocks form at the foot of the cliffs, just as in the case of frost-made talus, and this work goes on in all arid regions which have hot days and cool nights. The agency is purely mechanical and effects no chemical change; it is also entirely superficial and is prevented by even a thin covering of soil.

The work of destruction due to changes of temperature goes farther than merely splitting blocks off the faces of cliffs, and may result in breaking up a rock into minute fragments. Comparatively few rocks are made up of a single mineral, and in many rocks several varieties of minerals occur. Each of these minerals will expand and contract, when heated or chilled, at a slightly different rate from the others, and thus the particles are subjected to stresses which will gradually loosen them, causing the rock to disintegrate.

4. WIND

Of itself the wind is unable to accomplish in any important degree the disintegration of firm rocks, but when it can drift along sand and fine gravel, it may effect much. Except on sandy coasts, this agency is of small importance in regions of ordinary rainfall, because in these the soil is protected and held together by its covering of vegetation. In arid regions and deserts, on the contrary, high winds sweep along quantities of sand and fine gravel, which are hurled against any obstacle and gradually cut it away.

Very hard rocks yield but slowly to the cutting action of wind-driven sand, and in them the chief effect to be observed is a scratching and polishing of the surface. The same principle is employed in the sand-blast, which is a jet of sand, driven at a high velocity and used to engrave glass, polish granite, and do other work of the kind. Soft rocks are quite rapidly abraded and cut down by the drifting sand, and go to increase the mass of cutting material. The softer parts are cut away first, leaving the harder layers, streaks, or patches standing in relief. In this way very fantastic forms of rocks are frequently shaped out; pot-holes and caverns are excavated by the eddying drift, and archways cut through projecting masses.

As the wind does not lift the harder and heavier particles to any great height, the principal effect is produced near the level of the ground, and thus masses of rock are gradually undermined and fall in ruins, which in their turn are slowly abraded. Isolated blocks are sometimes so symmetrically cut away on the under side, that they come to rest upon a very small area and form rocking-stones, which, in spite of their size and weight, may be swung by the hand.

The fine particles abraded from the rocks by drifting sand have undergone no chemical change, the process being entirely mechanical.

The abrading effects of wind-driven sand may be observed in any desert region where naked rocks are exposed, as for example in the arid parts of Utah and Arizona. One very characteristic effect of this natural sand-blast is found in the appearance of the pebbles shaped by it. Pebbles of very hard and homogeneous materials, such as quartz or chalcedony, are highly polished. Those made from igneous rocks have the softer minerals worn away, leaving the harder to stand in relief in curious patterns, while limestone is carved into beautiful arabesques.

We have seen that the rain is slowly shifting the soil seaward, and in dry countries the wind acts in similar fashion. Strong winds, blowing steadily in one direction, carry great quantities of dust and fine sand with them, sometimes directly into the sea or other bodies of water, sometimes into rivers, or again to moister regions, where it comes under the influence of the rain.

Slowly as they work, the wind and temperature changes prevent any complete stagnation in the circulation of material, and thanks to them, the processes of disintegration of rock and transportation of soil are kept up even in the dryest deserts.

CHAPTER V

DESTRUCTIVE PROCESSES — RUNNING WATER

THE source of all running water, whether surface or underground, is atmospheric precipitation in the form of rain or snow. All springs and streams are merely rain (or snow) water collected together and fed from reservoirs. Of the rain-water which falls upon the land, about one third is evaporated, a second third flows over the surface to the nearest water-course, and the remainder sinks into the soil to a greater or less depth, and though part of it again comes to the surface in springs, yet a great portion must reach the sea by subterranean channels.

1. UNDERGROUND WATERS

The flow of underground waters, as well as that of surface waters, is determined by gravity, but surface topography has no effect upon it, and often the superficial and subterranean flows are, for considerable distances, in exactly opposite directions. Underground drainage is determined by the inclination of the rocks, the alternation of porous and impervious beds, the number and character of their joints and fissures, for the flow is ordinarily through these crevices, except in very porous materials, such as loose sand, which allow of a flow through their substance. In soluble rocks the water may dissolve out its own channels.

These facts of the underground movement of water are of great practical importance in all questions of drainage and water supply. Serious evils have followed from the careless assumption that subterranean drainage would be in the same direction as that on the surface of the ground. The accompanying diagram shows an arrangement of cess-pool and well, which was planned on the assumption that because the former was farther down the hill, it could not contaminate the latter. But the inclination of the rocks is such that the cess-pool would drain as directly into the well as though a pipe connected them. Underground waters perform the work of rock disintegration, both chemically and mechanically, but as the movement of such waters is usually extremely slow, the mechanical work is of very subordinate importance.

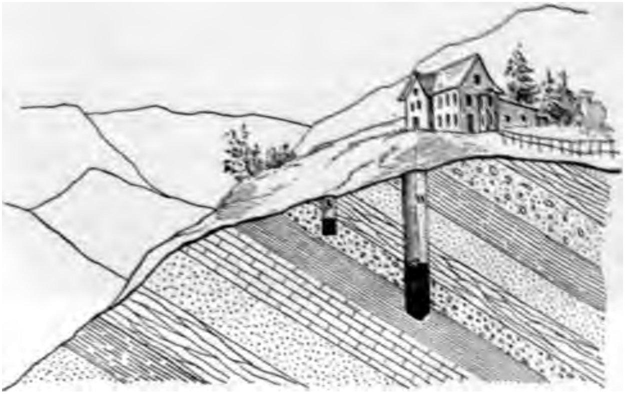

FIG. 28. — Diagram illustrating how surface and underground drainage may be in opposite directions.

In considering the effects of the rain we learned that its chemical efficiency is much increased by the humous acids which it takes up on passing through the soil. The water, making its way downward through the rocks, by means of the joints and bedding planes, exerts its slowly dissolving and decomposing effects upon the walls of these crevices. Such water therefore always contains more or less mineral matter in solution, the nature and quantity of which depend upon the character of the rock traversed.

In passing through limestones, percolating waters produce remarkable effects, owing to the solubility of the rock. From the surface sinkholes and pipes are dissolved downward, while in the mass of the rock caverns are dissolved out, often, as in the Mammoth Cave of Kentucky, many miles in extent and with rivers of considerable size flowing in them. Indeed, in limestone regions the smaller streams are generally engulfed and flow for a longer or shorter distance underground. When the roof of a cavern is no longer able to support itself, it falls in and exposes a ravine. Any portion of the roof which remains standing will then form a bridge, examples of which are the famous Natural Bridges of Virginia and of the Tonto Basin in Arizona.

Nothing is known as to the limits of depth to which the percolating waters may penetrate the crust of the earth, but so far as borings and deep mines have gone, water is always found, and the limit is probably far below any yet reached artificially. As the temperature of the earth increases downward, a level must be attained (probably at no very great depth) where the rocks become too hot to allow any further penetration, and at such depths the great pressure of the overlying masses must tend to close up the joints and crevices through which the water descends. The moisture in deep-seated rocks must be, for the most part, stationary or subject only to very slow fluctuations, for such rocks are solid and undecomposed. Even beds of rock salt, which would surely be dissolved away by moving water, are found at depths which can be reached by mining or boring.

When underground waters become highly heated by descending to great depths along channels which admit of a return to higher levels, or by coming in contact with masses of hot lava, their solvent efficiency is greatly increased. Rocks penetrated by such *thermal waters* are often profoundly altered in their character and composition. In igneous rocks so treated the complex minerals which make up these rocks are decomposed into simpler or more stable compounds. The felspars become opaque from the formation of kaolin, or are transformed into hydrated mica; minerals containing iron and magnesia give rise to chlorites (p. 21), serpentine (p. 22), and the like, while the lime compounds are converted into the carbonate and carried away in solution. Some of the minerals are altered in place, and others are deposited in the fissures and cavities of the rock. Thermal waters also alter the character of rocks by bringing in new from elsewhere. In the Yellowstone Park the great ss, which has been trenched by the Yellowstone Cañon,

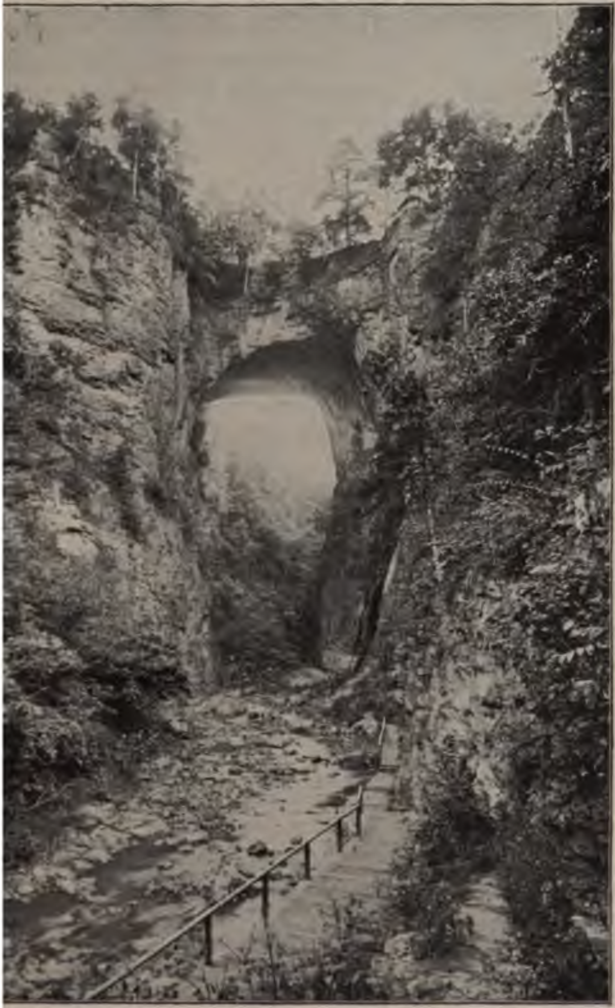

FIG. 29. — Natural Bridge, Virginia. (U. S. G. S.)

has been profoundly altered and decomposed by the action of the heated waters which traverse it.

Except in limestone caverns, underground waters seldom flow with sufficient velocity to accomplish much in the way of direct mechanical erosion, but indirectly they bring about mechanical changes of some importance. Slopes of earth or talus blocks lying on hillsides or mountains, saturated by long-continued, heavy rains, may have their weight so much increased and their friction so reduced, as to glide downward in landslips, which in inhabited regions are sometimes very destructive. Of this kind was the great landslip which occurred in the White Mountains (New Hampshire) in 1826.

Landslips may also occur when the rocks forming a slope are inclined in the same direction as that slope; the surface layers weighted with water, and especially if underlaid by clay-beds, which when lubricated with water become very slippery, may glide down the slope into the valley below. Mountain valleys in all parts of the world show plain evidence of such landslips, and the amount of rock thus displaced is sometimes very great. The landslip which occurred at Elm, Switzerland, in 1881, is estimated to have carried down more than 12,000,000 cubic yards of rock for a distance of 2000 feet.

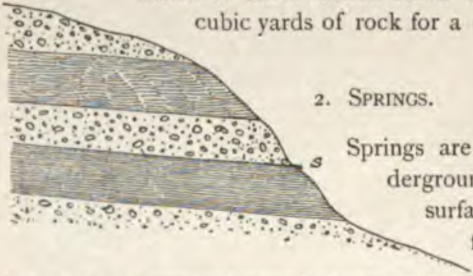

FIG. 30. — Arrangement of strata which causes hillside springs. The lower close-lined bed impervious.

2. SPRINGS.

Springs are the openings of underground streams upon the surface, and could not be formed were the land perfectly free from irregularities, for gravity controls the movement of underground waters, and the source of a spring must be higher than its mouth. It must be remembered, however, that a subterranean stream is often confined as in a pipe, and that the pressure to which it is subjected may seem to make it flow upward, as when a spring rises from a deep fissure, or bursts out upon the top of a hill. But these are not real exceptions, and here also the source, which may be many miles distant, is above the spring, and it is this which produces the necessary pressure.

The commonest type of spring is formed when a relatively impervious bed of rock (usually clay in some form) overlaid by porous rocks, crops out on a hillside. The rain-water descends through the porous beds, saturating their lower layers, until its descent is arrested by the impervious bed, and then the water follows the upper surface of the latter. When, by some irregularity of the ground, the impervious bed comes to the surface, the water will issue as a spring, or a line of springs. (See Fig. 30.)

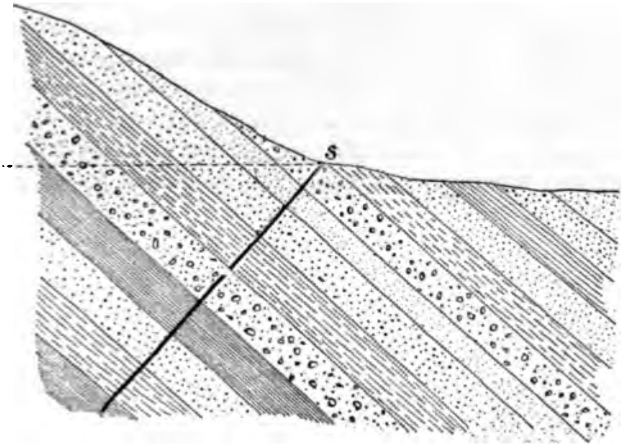

FIG. 31.— Diagram of fissure-spring. The heavy line represents the fissure along which the water rises.

A second class of springs are those which rise through a crack or fissure in the rocks. Inclined porous beds, enclosed between more impervious ones, allow the water to follow them downward, until in its lower course such water is under great pressure, or "head." On reaching a fissure opening upward, the water will rise through it and, if under sufficient pressure, will come to the surface.

An artesian well is a boring which taps a subterranean stream or sheet of water, confined under sufficient pressure to rise to the surface, or even spout above it, like a fountain. Artesian wells form most valuable sources of water supply, and it is important to understand the conditions under which they may be successfully bored. Many people have the impression that a boring anywhere, if deep enough, will furnish artesian water, and much money has been wasted by making this assumption. The only safe guide is a careful examination of the geological structure of the region, and failure may result even when everything seems favourable.

The structural requisites for successful borings are as follows: (1) There must be a porous water-bearing stratum, usually sand or sandstone, enclosed between relatively impervious beds. The impervious beds are necessary to enclose the porous beds and prevent the water from escaping either upward or downward, shutting it in as in a closed pipe, or underground siphon. (2) At some point, which must be above the mouth of the well, the porous stratum must reach the surface, so that it may receive its supply of rain-water. If all the points where the porous bed crops out be above the mouth of the proposed well, the conditions are particularly favourable, because none of the water can escape, except by very slow percolation through the relatively impervious beds. If the water-bearing stratum communicates with the surface at a level lower than the site of the well, success will depend upon the ease with which the water can escape at the lower level. The best conditions for a flowing well are, therefore, to be found in a basin of folding, with the strata dipping toward the well from all directions, and the porous bed cropping out around the edge of the basin, at levels much above the mouth of the well.

The outcropping edges of the porous strata may be very far, even hundreds of miles, from the well; the water will follow the dip of the beds and rise to the surface wherever it is tapped, provided that there is no easier path of escape. The friction of the slow creeping through the water-bearing bed is so great that a spouting well never throws the water up to the level of the outcrop.

The quantity of water which can be annually drawn from an artesian reservoir cannot exceed the annual supply through rainfall, though, at first, the stored water will cause a more abundant flow. When several wells are bored near together, each new well is apt to diminish the flow from the older ones, though the total discharge from all the wells increases until the limit of supply is reached. New wells at lower levels may take all the water and leave none for those at higher levels.

While the basin-like arrangement of strata is the most favourable, it is not necessary. Along the New Jersey coast is a great thickness of alternating beds of sands and clays, all dipping gently toward the sea. Aside from levels of minor importance, no less than six separate porous layers afford abundant supplies of water, which are now very largely drawn upon.

The depth necessary to obtain flowing wells differs, of course, with the topography and structure of the country. In North Dakota, for example, flowing wells have been obtained at depths varying from less than 100 to more than 1500 feet. The Cretaceous sandstone which underlies immense areas of the Great Plains region is the principal source of supply.

In limestone districts ravines may intersect the course of considerable underground streams, which thus reach the surface in springs of unusual volume. A very striking and beautiful example is the Giant Spring in the cañon of the upper Missouri, near Great Falls, Montana.

Springs, as such, do little in the way of rock disintegration, but they accomplish something by undermining the rocks at the point where they issue, and thus working their way backward. This process is known as the *recession of spring-heads*. The underground streams, of which springs are the outlets, have often effected much in the way of dissolving rock-material, and hence spring-water always contains dissolved minerals, principally the carbonates and sulphates of lime and magnesia, and the chlorides of magnesium and sodium. In mineral springs the quantity of dissolved materials is larger and perceptible to the taste.

Thermal Springs are those whose temperature is notably higher than that of ordinary springs in the same region, and they range from a luke-warm to a boiling state. This increase of temperature may be caused in either of two ways: (1) In volcanic regions, water coming into contact with uncooled masses of lava is highly heated and reaches the surface as a hot spring. Of this class are the innumerable thermal springs of the Yellowstone Park. (2) Wherever the disposition of the rocks is such that water may descend to great depths within the earth and yet return to the surface by hydrostatic pressure, thermal springs appear. These conditions are found only in regions where the rocks have been much folded and fractured. In this case the temperature of the water is raised by the interior heat of the earth, which, as we have seen, increases with the depth. Springs of this class occur numerously along the Appalachian Mountains, and in larger numbers and of higher temperatures they accompany the various ranges of the Rocky Mountains and Sierra Nevada.

Geysers are thermal springs which periodically erupt, throwing up hot water in beautiful fountains, accompanied by clouds of steam. Though of great scientific interest, geysers are not important geological agents, because of their rarity, since they occur only in Iceland, the Yellowstone Park, and New Zealand.

The destructive effects of thermal springs are principally accomplished below the surface, and have already been considered under the head of underground waters. The high percentages of dissolved materials which such springs usually contain are evidence of the important work of rock disintegration which they perform.

3. RIVERS

The destructive work of rivers, including in that term all surface streams, is far less extensive, in the aggregate, than that of the atmospheric agencies, but because the work of a stream is concentrated along its narrow course, it appears much more striking and impressive.

The chemical disintegration performed by rivers is of no great amount, though, of course, some soluble materials are withdrawn from the rocks, over which the waters flow. In limestones this may be considerable, especially if the water be charged with organic acids from a swamp or peat-bog.

The mechanical work of a river is much greater than the chemical, and is dependent upon the velocity of the current, varying directly as the square of that velocity. The velocity of a stream is the rather complex resultant of several factors, the chief of which is gravity; the steeper the slope of the bed, the swifter the flow of the water. A second factor is the volume of water, the velocity varying as the cube root of the volume. That is to say, if one of two streams which flow down the same slope has eight times as much water as the other, it will flow twice as fast. Other factors enter into the result, but slope of bed and volume of water are much the most important.

Pure water can do little to abrade hard rocks, though it can wash away sand, gravel, and other loose materials. As in the case of the wind, the stream merely supplies the power; the implement with which the cutting is performed is the sand, pebbles, and other hard particles, which the water sets in motion. These abrade the rocks against which they are cast, just as the wind-driven sand does, but more effectively, because of the ceaseless activity of the stream, and because many rocks are rendered softer and more yielding by being wet. The cutting materials are themselves abraded and worn finer and finer by continued friction against the rocks and against one another. In the case of complex minerals this abrasion is accompanied by more or less chemical decomposition, as has been shown experimentally by rotating crystals of felspar in a drum half filled with water. When the felspar was ground down to mud, the water showed the presence of potash and soda in solution.

A river which is subject to sudden fluctuations of volume, being now a rushing torrent and again almost dry, is a much more efficient agent, both of erosion and of transportation, than is one which carries nearly the same quantity of water at all times, or which fluctuates only slowly.

Since the velocity of a stream is so largely dependent upon gravity, it is obvious that the deeper a stream cuts its channel, the less steep does its slope become, and that so long as the region is neither upheaved nor depressed, the river performs its vertical erosion at a constantly decreasing rate. Unless, therefore, the work is done under very exceptional conditions, as in the case of the Niagara, we cannot reason from the present rate of excavation to the length of time involved in cutting out a given gorge.

Unless the region through which a river flows is upheaved, and thus, by increasing the fall, renewed power is given to the stream, a stage must sooner or later be reached when the vertical cutting of the stream must cease. This stage is called the *base-level of erosion*, or *regimen* of the river, and it approximates a parabolic curve, rising toward the head of the stream. Elevation of the country will start the work afresh, until a new base-level is reached, while depression will have a contrary effect and may put a stop to vertical erosion where it was in active progress before. When the base-level is reached, the river cuts laterally, undermining its banks and working like a horizontal tool upon the country-side.

So long as the slope of the bed is steep, the river runs swiftly and with a comparatively straight course; when lower slopes are reached, the stream begins to meander, and shift its channel about, undermining its banks, cutting them away in one place and building them up in another, and forming a wide plain.

Having learned the general character of river erosion, we may illustrate it with a few concrete examples.

1. A particularly interesting case is that of the little river *Simeto* in Sicily, since the history of its gorge is so well known. In 1603 a great lava flood from Ætna was poured out across the course of the stream, and, when cold, solidified into a barrier of the hardest rock. When Sir Charles Lyell visited the spot in 1828, he found that in a little more than two centuries the stream had cut a gorge through this barrier of 40 to 50 feet deep, and varying in width from 50 to several hundred feet. The lava which had thus been trenched is not porous or slaggy, but homogeneous and dense.

2. In the northern parts of the United States the great ice-sheet, which in late geological times covered the country, brought down with it vast quantities of drift, that filled up the channels

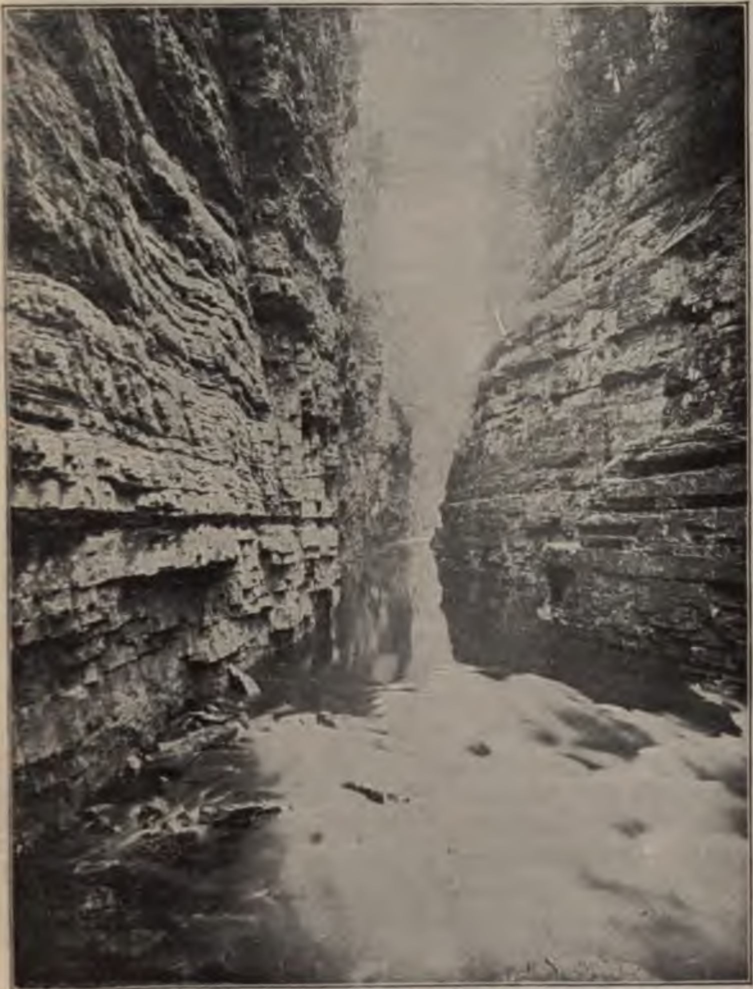

FIG. 32. — The Au Sable Chasm, N.Y. (Copyright by S. R. Stoddard, Glens Falls, N.Y.)

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of many streams and quite revolutionized the drainage of certain districts. Since that time the displaced streams have cut out new channels for themselves, often through hard rocks, and many now flow in quite deep gorges, with nearly vertical walls. Au Sable Chasm, New York, is an example of these geologically modern river gorges, the atmosphere not having had time to widen it.

3. The Niagara is an exceptional case, the gorge being cut, not only by the direct abrasion of the running water, but also by the action of the spray and frost at the falls. In the ravine the upper rock is a hard, massive limestone, which is underlaid by a soft clay-shale. The latter is continually disintegrated by the spray of the cataract and by the severe winter frosts, undermining the limestone, which, when no longer able to bear its own weight, breaks off in tabular masses. Thus the falls are steadily receding, leaving behind them a gorge, which is deepened by the river.

4. The most remarkable known examples of river erosion are the cañons of the Colorado. The Grand Cañon is over 200 miles long and from 4000 to 6500 feet deep, with precipitous walls. It is extremely probable that the river has been rendered able to cut to such profound depths by the gradual uplifting of the whole region, which is now a lofty plateau, in places more than 8000 feet above the sea. The erosive power of the river has thus been continually renewed and a more or less uniform rate of excavation secured. (See Frontispiece.)

Transportation by Rivers. — The main importance of rivers as geological agents is not their work of erosion, but lies rather in what they accomplish as carriers of the results of their own destructive activity and that of the atmosphere, comprising both the materials which are mechanically swept along in suspension and those which are carried in solution.

Materials in Suspension. — The transporting power of running water is dependent upon the velocity of the current, and both mathematical and experimental treatment of the problem brings out the surprising result that the transporting power varies directly as the sixth power of the velocity. If the rapidity of a stream be doubled, it can carry 64 times as much as before. The destructiveness of sudden and violent floods is thus explained. In the terrible flood which overwhelmed Johnstown, Pennsylvania, in 1889, great locomotives and massive iron bridges were swept off, it is hardly an exaggeration to say, like straws, and huge boulders carried along like pebbles.

It obviously follows from the relation obtaining between velocity and transporting power, that a slight increase in the rapidity of a stream will largely augment the load which it carries, provided the stream obtains as much material as it can carry, while a slight reduction of velocity will cause the deposition of a large part of that load. The buoyancy of water adds, in an important degree, to its ability to sweep along sediment, because when any substance is immersed in water, it loses weight to an amount equal to the weight of an equal bulk of water. The specific gravity of most rocks is from two and one-half to three, so that when immersed they lose from one-third to two-fifths of their weight in air. The shape of the fragments is likewise a factor in determining the velocity requisite to move them; the larger the surface of the fragment in proportion to its weight, the more easily it is carried in suspension. Thus flat grains or scales are carried farther than round ones; while, on the other hand, rounded fragments are more easily rolled along the bottom, when too heavy for the current to lift.

The greater part of the débris or sediment which a stream carries is furnished to it by the destructive activity of the atmosphere; the rains wash in the finer materials, while frost and landslips bring in the larger masses which are carried down by mountain torrents. To this material the river adds that which is derived from its own work in the cutting away of its banks and bed.

Materials in Solution. — In addition to what the river carries down mechanically in suspension or sweeps along the bottom, there is a third class of material; namely, that which is dissolved in the waters of the stream. Dissolved matters are always present in greater or less quantity, and are the same in kind as those which we have already found to occur in spring-waters, whence they are, for the most part, derived by the rivers. River-water is, however, usually more dilute than that of springs, because of the rain which falls into it, or pours in from the banks. In very dry regions, where this additional rain supply is at a minimum, and where the streams are concentrated by continual evaporation, they are frequently undrinkable, on account of the quantity of matters in solution which they contain. Examples of this are the salt and so-called "alkali" (a very comprehensive term) streams of the arid West, which contain a great variety of dissolved minerals.

The quantity of material which rivers are continually sweeping into the sea, is enormously great. Every year the Mississippi carries into the Gulf of Mexico nearly 7,500,000,000 cubic feet of solid sediment, either in suspension or pushed along the bottom, an amount sufficient to cover one square mile to a depth of 268 feet. In addition to this is the quantity brought down in solution, which is estimated at 2,850,000,000 cubic feet annually.

Different rivers vary much in the proportion of suspended and dissolved materials which they carry and discharge into the sea; a roughly approximate average makes the amount of material removed equal to about 11,400 cubic feet (600 tons) of annual waste for every square mile of the land surface of the globe; that is, *under existing conditions* of slope, temperature, rainfall, etc. How great a difference in the result a change in these factors may produce, will be seen from a comparison of the Mississippi and the Ganges. The amount of suspended matter discharged by the former represents a lowering of the surface of the entire drainage area at the rate of one foot in 4920 years, while in the case of the Ganges it is one foot in 1880 years, or more than twice as fast. The amount of material carried by the Amazon has not been determined, but there can be little doubt that it is far greater than that discharged by the Mississippi. The area drained by the Amazon is less than twice as large as the drainage basin of the Mississippi, and yet it brings to the sea five times as much water as does the great river of North America.

The total amount of material which has been removed from the land surfaces by the atmospheric agencies and carried to the sea by rivers is incalculably great. The Appalachian mountain system has thus lost thicknesses of rock which vary in different regions from 8000 to 20,000 feet, and it is altogether probable that the average waste of all the continents amounts to several thousands of feet. The figures given for the basins of the Mississippi and the Ganges show that such wastes imply enormously long periods of time.

CHAPTER VI

DESTRUCTIVE PROCESSES—ICE, THE SEA, LAKES

Glaciers are much the most important form of ice as a geological agent. A glacier is a stream of ice which flows *as if* it were a very tough and viscous fluid, and does not merely glide down a slope, as snow slides from the roof of a house. Glaciers play a very important part in keeping up the circulation of the atmospheric waters, and produce geological results of an extremely characteristic kind. Their contribution to the sum total of rock destruction and reconstruction is, it is true, relatively small, but it often becomes important to trace the former extension of glaciers, which, in its turn, has a wide bearing upon some of the most far-reaching of cosmical problems.

As we ascend into the atmosphere from any point on the earth's surface, we find that it becomes continually colder with increasing height. In this ascent a level is eventually reached, where the temperature of the air never rises for any length of time above the freezing-point, and above this level no rain, but only snow falls. This level is called the limit of perpetual snow, or simply the snow-line. While the height of the snow-line above the sea-level is, like climate in general, much affected by local factors, yet, speaking broadly, its elevation is determined by latitude. In the tropics the snow-line is 15,000 or 16,000 feet above the sea, descending more and more, as we go toward the poles, and coming down to sea-level within the polar circles.

Were there no means of bringing the snow which accumulates above the snow-line to some place where it may melt, it would evidently gather indefinitely, and at last nearly all the moisture of the earth would be thus locked up. As a matter of fact, there is no such indefinite accumulation. In very dry regions the excess of snow is disposed of by direct evaporation, and on high mountains avalanches carry the snow down to lower levels, where it melts. Where the snow-line is at sea-level, avalanches are obviously of no avail. In places where the excess of snow cannot be disposed of in either of these ways, glaciers are formed and thus keep up the circulation of the waters, by carrying the surplus snow down to lower levels at which it can melt, or by entering the sea and in the shape of icebergs (which are fragments of glaciers) being floated to warmer latitudes.

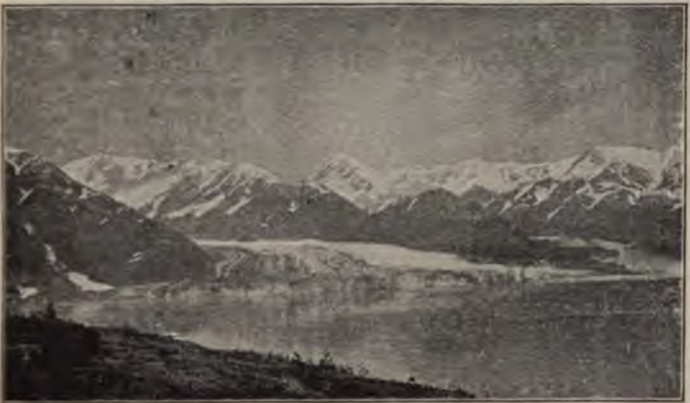

FIG. 33. — The Dalton Glacier, Alaska. (U. S. G. S.)

Though even at the present time there are in various parts of the world great tracts of glacier-ice, they cannot be called common and are found only where certain conditions concur. The nature of these conditions will be best understood by examining the process of glacier formation.

Snow is made up of minute, hexagonal crystals of ice, which are intimately mixed with air and thus separated from one another. Though the individual crystals are transparent, snow is white and opaque, as always results when a transparent body is intimately mixed with a gas, as in the foam on water, or in powdered glass. Ice is composed of the same kind of crystals as is snow, but they are in contact with one another, not separated by air. To convert snow into ice, therefore, it is only necessary to expel the air and bring the crystals into contact, for which pressure alone is not ordinarily sufficient.

The first step in the transformation is the partial melting of the upper layers of snow, for which a change of temperature is necessary, though the change need not warm the air, but may be due to the direct rays of the sun. Glaciers are rare in the tropics because of the constancy of the temperature, and the small area which extends above the snow-line, which seldom permits the formation of extensive snow-fields. Sometimes, however, the conditions of glacier formation are fulfilled even in the equatorial zone; for example, there is a glacier on one of the peaks of Ecuador.

When the surface layers of snow have been partially melted, the water thus formed trickles down into the snow beneath, expelling much of the air. This underlying snow has still a temperature much below the freezing-point, and the percolating water is soon refrozen into little spherules of ice. This substance, midway between snow and ice, is called *névé*, and may be seen every winter wherever the snow lies for any length of time. The hardened "crust" which forms by the refreezing of partly melted snow is névé. The air, which is now in the form of discrete bubbles, is largely expelled by the increasing pressure of the overlying snow masses, which are continually added to by renewed falls, and the névé is thus converted into ice.

It follows from this that glaciers can be formed only where there is a relatively large snow supply, or at least where the snow accumulates to great thicknesses, and cannot be disposed of by either melting or evaporation. Hence, glaciers are rare or absent in dry regions, where the snow does not increase to great depths, as in most of the Rocky Mountains within the limits of the United States. It also follows that the ground upon which the snow lies must be so shaped as to allow great masses of it to gather, without rushing downward in avalanches.

Wherever, then, more snow falls in winter than can be melted in summer, and continues to accumulate, glaciers will be formed.

A glacier moves in much the same way as a river, but at a very much slower rate. The centre moves faster than the sides, because the latter are retarded by the friction of the banks, and, for the same reason, the top moves faster than the bottom. While behaving like a plastic substance under pressure, ice yields readily to strain, and even a slight change in the slope of the bed will cause a great transverse crack, or *crevasse*, to form, which, like an eddy in a stream, seems to be stationary, because always formed again at the same spot. Other systems of cracks, the marginal crevasses, are formed along the sides of the glacier, and are due to the more swiftly moving centre pulling away from the retarded sides.

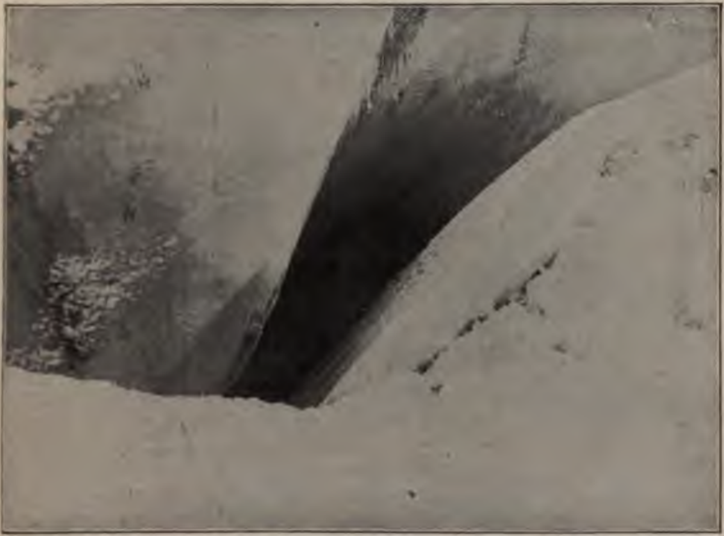

FIG. 34.— Crevasse in a glacier, partly concealed by a snow-bridge.

The rate of glacier movement depends upon the snow supply, upon the slope of the ground, and the temperature of the season. The comparatively small glaciers of the Alps move at rates varying from two to fifty inches per day in summer and at about half that rate in winter, while the vastly larger glaciers of the polar lands have a correspondingly swifter flow. The great stream of ice which enters Glacier Bay in Alaska has a summer velocity of seventy feet per day in the middle.

Southeastern Alaska is a region where glaciers are developed on a very extensive scale. The Malaspina is an immense ice-sheet, having an area of 1500 square miles, which is formed at the foot of the St. Elias Alps by the confluence of several great glaciers from the neighbouring mountains. Parts of this vast accumulation of ice are stagnant and deeply covered with rock débris, upon which there is a luxuriant growth of vegetation, with not less than 1000 feet of ice beneath it.

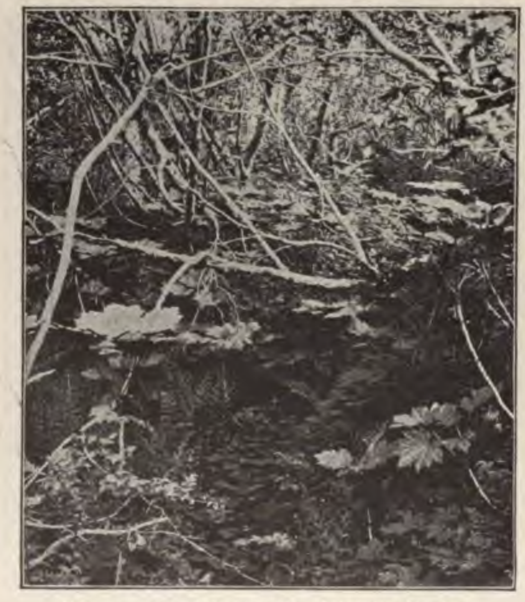

FIG. 35. — Vegetation on the Malaspina Glacier. (U. S. G. S.)

In Greenland and the Antarctic continent the accumulations of ice are on a scale not elsewhere found, and these regions present conditions of great geological interest. Greenland, except for a narrow strip along the coasts, is buried beneath a vast ice-sheet, which can hardly be less than 2000 or 3000 feet thick, and from which great glaciers descend eastward and westward to the sea. In the interior only a few isolated mountain peaks, or *nunataks*, rise through the ice mantle; except for these, nothing is visible but illimitable fields of snow. The snowfall is not very great; but so little of it is disposed of by evaporation or melting, that there is a large excess which goes to the growth of the ice-sheet, and keeps up the supply for the innumerable glaciers which flow to the sea.

The source of a glacier is always above the snow-line, but the ice-stream itself may descend far below that line, slowly melting and diminishing in thickness as it flows. The lower end is at the point where the rate of melting and the rate of flow balance, so that changes in the temperature of the seasons or in the amount of the snow supply will cause the glacier to advance or retreat, as one or other of these factors prevails. Thus the Alaskan glaciers have retreated notably within the last century, while some of the Norwegian ones are advancing. From the lower end of a glacier there always issues a stream of water, which flows under the ice, often in great volume, and even in winter, for the thick ice is a non-conductor and protects the stream from the intense cold of the air.

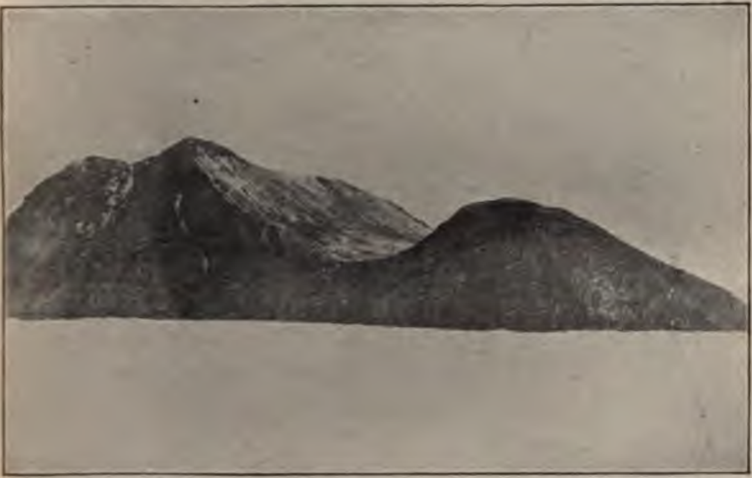

FIG. 36. — Nunatak rising through the ice-cap, Greenland. (Photograph by Libbey.)

The glaciers mentioned are examples of the various forms of moving bodies of land ice. We have (1) *Alpine glaciers*, of which those in the Alps are types, and are relatively small streams occupying narrow mountain valleys. (2) *Piedmont glaciers*, like the Malaspina of Alaska. These are great accumulations or lakes of ice which form at the foot of mountains, by the coalescence of numerous glaciers of the Alpine, or valley type. (3) *Continental glaciers* are those which cover enormous areas of land, such as the ice-sheet under which nearly all of Greenland is buried and that which covers the Antarctic land. This is a type of especial interest and significance to the geologist, because of the light which it throws upon the often mysterious operations of the ice-sheets which once covered large portions of North America and Europe.

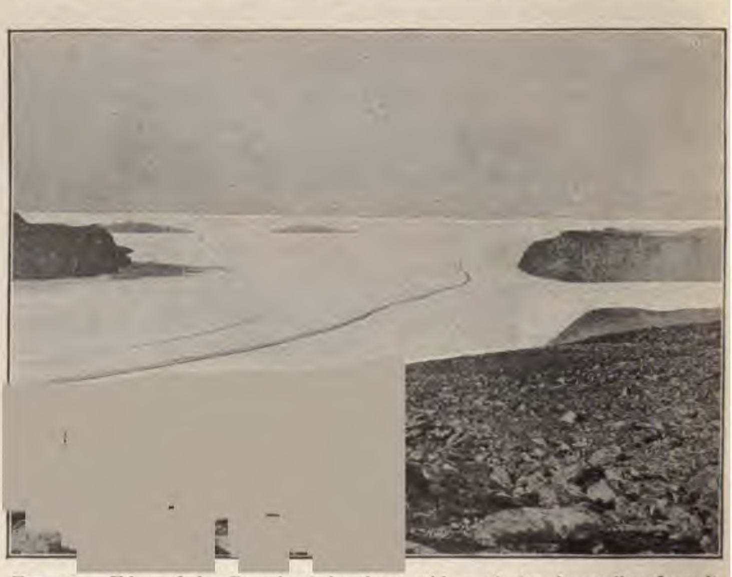

FIG. 37. — Edge of the Greenland ice-sheet, with a glacier descending from it. The dark line is a medial moraine. (Photograph by Libbey.)

Glacier Erosion is highly characteristic, and enables us to detect the former extension of ice streams which have greatly shrunken and the former presence of them in regions whence they have long vanished. The erosive capabilities of moving ice have been and still are the subject of dispute, but much remains that cannot be questioned. Thick glaciers, moving with comparative rapidity down the steeper slopes, will sweep away the soil and other loose materials which cover the ground. The surface is

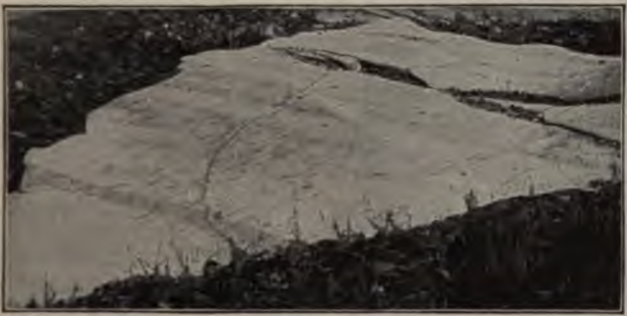

FIG. 38. — Rock polished by glacial ice, near Englewood, N.J. (Photograph by Salisbury.)

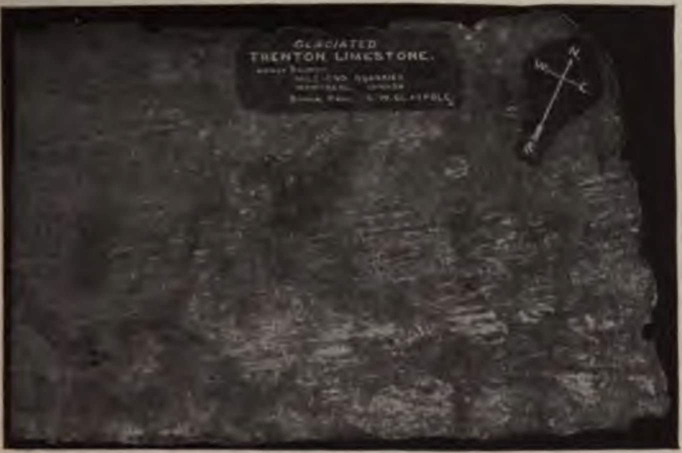

FIG. 39. — Scored and smoothed limestone from Montreal, Canada.

thus, in the first instance, rendered more irregular than before, because the hollows formed by the varying depths to which atmospheric disintegration descends (see p. 78) are cleared out and the rocks laid bare.

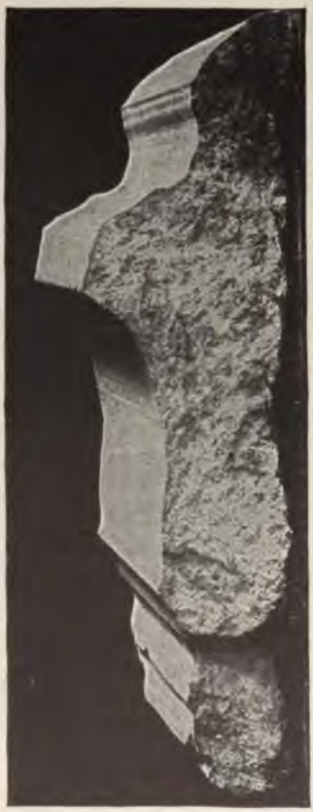

FIG. 40. — Side of trough cut by glaciers in the limestone of Kelly's Island. (From a specimen in the U. S. National Museum.)

Bare rocks, when exposed to the action of the moving ice, are ground down, scored, polished, and rounded in a way that can be accomplished by no other agent, and which is the unmistakable autograph of the glacier. Stones of all sizes, pebbles, sand, and dust, make their way from the surface to the bottom of the glacier through the crevasses, while others are picked up from the bed. These hard pieces are firmly held by the great weight of the ice, and are slowly pushed along over the rocky bed with irresistible power, cutting grooves of a size corresponding to the fragments which do the work. Fine particles make hair-like scratches, large boulders cut deep troughs, such as the remarkable ones found on Kelly's Island in Lake Erie; but all, whether coarse or fine, are in the direction of the glacial flow and keep parallel, often for considerable distances.

The smaller particles, earth and sand, and those which are made by the abrasion of the bed, act as a polishing powder, and if the rocks of the bed are sufficiently hard, they will be finely polished. Hummocks of rock, over which the ice passes, are worn down and rounded into the form called "*rôches moutonnées*," with the side upon which the ice impinged gently sloping and polished, but with the down-stream side abrupt and often not ice worn.

On a large scale, glacial erosion produces rounded and flowing outlines of hill and valley, cutting hard and soft rocks alike (instead of leaving the harder standing in relief), and producing forms which are in marked contrast to the craggy and rough topography of unglaciated regions.

River action may polish hard rocks by scouring them with sand, but the glacial furrows and parallel striæ cannot be imitated by other agents. To find these characteristic marks of ice, it is not necessary to visit actual glaciers; the northeastern quarter of the United States, from the Mississippi to the Atlantic, displays them in abundance, where harder rocks are exposed on the surface. The rounded forms, the parallel striæ, the polished surfaces, are common where the rocks are hard enough to retain the markings.

Glacier Transportation. — The transporting power of a glacier is not determined by its velocity, at least so far as the material carried on its surface is concerned. This is because the rocks may be regarded as floating bodies with reference to the ice, and thus a rock weighing many tons is carried with as much ease as a grain of sand. The masses of material transported by a glacier are known as *moraines*. The moraines which are carried on the top of the glacier are derived from the cliffs and peaks which overhang the ice, and the action of frost and landslips is continually showering down earth, sand, and rocks of all sizes, from small blocks up to masses the size of houses. This material is heaped up along the sides of the glacier in disorderly array, and here forms the *lateral moraines*. When a glacier is composed of branch streams, it will have a corresponding number of *medial moraines* (see Fig. 37), in the middle of the glacier. When two branches unite, their coalesced lateral moraines form a single medial moraine.

The quantity of material thus carried on the top of the glacier depends upon the amount of rock surface which extends above the level of the ice and is subject to the action of the ice and the atmosphere. In the Alps, where the glaciers flow in deep ravines, the moraines are large, and some of the great Alaskan glaciers have their lower reaches so covered with rubbish, that the ice is visible only in the crevasses. In Greenland, on the contrary, the inland ice-cap has very little material on its surface, because only scattered nunataks rise above it.

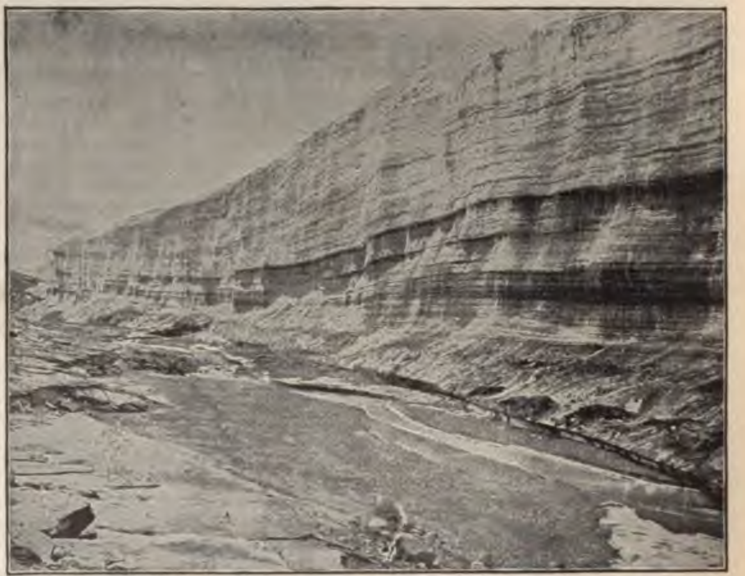

FIG. 41.—Front of Bowdoin Glacier, Greenland. The dark bands are made by englacial drift.

The substances frozen into the bottom of the glacier and pushed along over its bed form the *ground moraine*, and at the end of the glacier is the *terminal moraine* (see Fig. 57), where all the materials carried are dumped in a promiscuous heap, except so much as is swept away by the stream of water. Besides the moraines proper, there is a certain amount of *englacial drift*, carried in the body of the ice. This is derived from débris that comes from the surface, but does not work its way entirely to the bottom, as well as from that which gathers upon the surface of the snow or névé and is covered up by subsequent snowfalls. The materials carried by a glacier are as characteristic as the marks left upon the rocks over which the ice has flowed. Aside from the substances swept along by the sub-glacial stream, the various fragments are not rounded and water-worn, as is the sediment of rivers. The moraines on the top of the ice (lateral and medial) are little or not at all abraded, but are deposited as angular blocks and fragments. The ground moraine, on the other hand, is abraded in a peculiar way; the larger fragments retain their angular shape more or less distinctly, though the angles and edges are rounded off, and the side of the pebble or boulder which was in contact with the rocky bed is itself scored and polished. The finer fragments produced by the grinding and crushing of the rocks against one another are angular. In all this work of glacial denudation the process is entirely mechanical, — chemical disintegration plays no part in it.

Certain other forms of transportation by ice may be conveniently mentioned here.

Ground Ice forms in rivers and ponds on the bottom, freezing around stones and boulders, and when broken up by thaws, this ice may float for long distances, carrying with it burdens far greater than the stream which transports the ice could carry unassisted. The shores of the St. Lawrence River are fringed with lines of large boulders which have thus been brought down.

Coast Ice. — In Arctic regions the shallow water along the coast is frozen in winter into a broad shelf of ice called the *ice-foot.* In the spring landslips cover the ice with débris, while the bottom is studded with stones and pebbles. When the ice-foot is broken up in summer, part of it is drifted away and transports its load of rock for long distances. Other parts are worked backward and forward by the waves and tides, scoring the rocks of the coast and grinding and polishing the fragments of rock frozen in the ice, in much the same fashion as glacial pebbles are scored and ground. Over comparatively limited areas the marks of coast-ice often have a deceptive resemblance to those left by glaciers.

Icebergs. — When a glacier enters the sea, it ploughs along the bottom until the buoyant power of the water breaks off great fragments of it, which float away as icebergs. These are often of gigantic size, veritable islands of ice, and huge as they appear, only about one-ninth of their bulk is above water. As icebergs are derived from glaciers, they carry away whatever débris the parent glacier had upon or within it.

Begin

2. The Sea

The destructive work of the sea is accomplished mainly by means of the waves which the wind raises upon its surface. Ocean currents are, as a rule, so far from shore, and flow in such deep water, that their erosive power is comparatively small. The Gulf Stream is said to scour the bottom in the Florida Straits and off the Carolina coast, but this is exceptional.

Waves act continually upon all coasts, but with very different force at different times and places. According to observations made for the Scotch Lighthouse Board, the average wave pressure on the coast of Scotland is for the five summer months 611 pounds per square foot, and for six winter months 2086 pounds. These are average figures and are greatly exceeded in storms, when the force of the breakers often rises to many tons per square foot.

The effect produced by this great force depends upon the character of the rocks of the coast, its height, and the angle at which it rises out of the water. When the coast is high, steep, and rocky, the waves continually wear away its base, partly by dislodging the blocks into which all consolidated rocks are divided, and partly by using as projectiles the blocks which it has dislodged, or which have been loosened by the frost. In heavy gales great masses, weighing tons, it may be, are hurled with tremendous violence against the base of the cliffs, cutting them into caverns, which are further excavated by the ordinary surf. Eventually, the cliff is undermined, and the unsupported masses above fall in ruins.

Waves are not entirely dependent, as rivers are, upon the hard materials which they dash upon the coast for their efficiency as destructive agents. The force of the mere blow given by a storm breaker is very great, and the hydrostatic pressure which first forces the water into every fine crevice of the rock, and then withdraws it, together with the sudden compression and rëexpansion of the air contained in these fissures, assists materially in the loosening of the blocks.

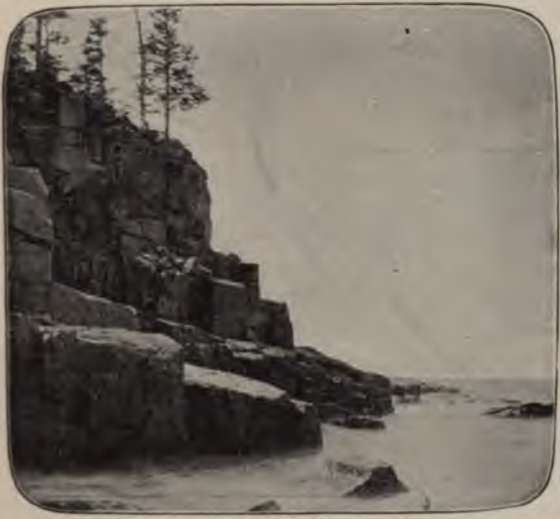

FIG. 42.—A rocky shore, coast of Maine. (Photograph by McAllister.)

Along coasts which are composed of hard rocks the work of cutting back the land by the sea is comparatively slow, but when the rocks are soft and yielding, and yet rise abruptly from the ocean, the waste is so rapid as to attract every one's attention. The coast of Yorkshire in England is washed away at an average rate of nearly seven feet per annum. The island of Heligoland near the German coast, which has now a circumference of less than three miles, in 1300 A.D. measured forty-five miles around. At

Long Branch, New Jersey, the sandy bluffs must be artificially protected against the attacks of the sea, yet in spite of such protection, almost every severe gale does considerable damage.

Sandy coasts which are low-lying and flat often suffer less from the inroads of the sea than rocky and precipitous ones, especially as they are apt to be lines along which material is accumulating. Even such coasts may, however, be rapidly cut back, as is shown in the familiar example of Coney Island, where great damage has been done of late years. When the sea is eating away a sandy shore, the homogeneous material prevents the occurrence of such irregularities of the coast-line as occur in rocky districts. Beside cutting back its shores, the sea continually grinds up the material which is brought into it by the rivers, and that which it obtains by its own wear of the coast. The great blocks on the shore are rolled about in storms, and worn into rounded boulders, which are gradually reduced to smaller and smaller size. All the minerals softer than quartz are rapidly ground into fine particles and swept

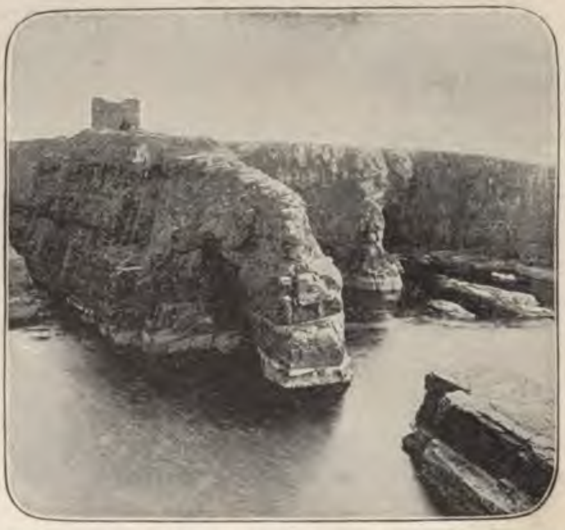

FIG. 43. — Coast of Scotland, showing effects of marine erosion.

away by the undertow into deeper and quieter waters, leaving the larger quartz fragments to form the pebbles and sand of the beach.

The action of the waves is limited vertically, ceasing to be effective in quite shallow water, not far below the low-tide mark. In violent storms the waves often accomplish much destruction far above high tide, but the principal work of the waves is confined to a belt extending from a little above high tide to a little below low tide. Below the latter, the wave work is often efficiently supplemented by tidal currents, which under favourable circumstances acquire great velocity and depth, scouring away loose materials and perhaps even cutting into solid rock. When an island of considerable extent is exposed to the incoming tide, the latter travels around the island in both directions, and if the shape of the mainland is favourable, one of these currents will be much higher than the other, which will produce a "race" between the island and the mainland. Hell Gate, New York, is an example of this; the tide advances through New York Bay and Long Island Sound, being higher at flood, lower at ebb in the sound than in the bay. The consequence is a swift current into the bay at flood tide and into the sound at ebb. By such means as this, the sea cuts away the land to depths much greater than unassisted waves can effectively reach.

The chemical disintegration due to the sea is not well marked in shallow waters, where the mechanical work is so much more effective and striking. In the profound depths of the oceanic basins, where the water is never disturbed and where its motion is extremely slow, chemical activity becomes relatively very important. Calcareous shells are completely dissolved, and the volcanic débris which covers the sea-bottom over vast areas, is disintegrated into a characteristic red clay.

Lakes.—In comparison with the long life of the earth, lakes must be regarded as merely temporary bodies of water, which will sooner or later disappear, either by being drained of their waters or by being filled up with the sediments which are washed into them. The general term *lake* is employed for any inland body of water, which does not form part of the sea, but lakes are formed in very different ways and have correspondingly different histories. Most lakes occupy depressions below the general drainage level of the country, whether these depressions be due to movements of the earth's crust, to glacial excavations, to unequal decomposition by the atmospheric agencies, or to some other factor. Others, again, are held back by dams, such as lava streams, glacial moraines, or the glaciers themselves, by the débris of landslips, or by the deltas of tributary streams which bring in more material than the main river can dispose of. Others still are enlarged basins cut out by rivers. Great lakes that persist for long periods of time are contained in basins, often of great depth, which were formed by movements of the earth's crust; the other kinds are more evanescent and usually of rather small size.

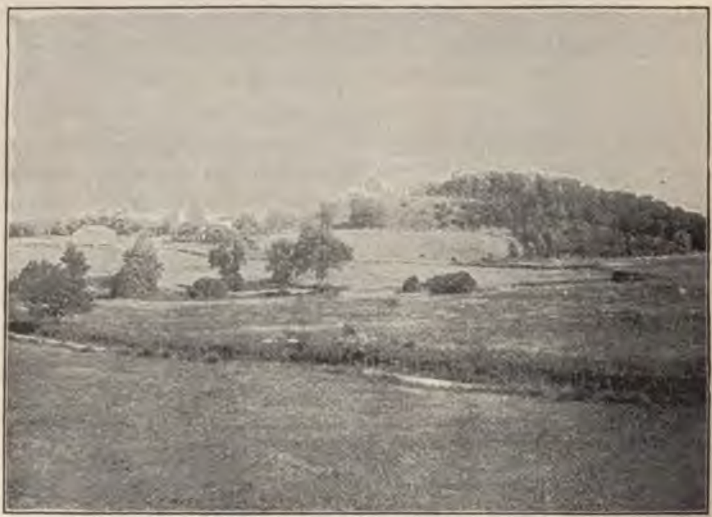

FIG. 44. — Old lake terraces, western New York. (U. S. G. S.)

Small lakes accomplish very little in the way of rock destruction, but are rather places of accumulation. The waves, even in storms, are not heavy enough to effectively cut back the shores, while the current of water through the lake is too slow and the sediment transported too small and light to erode the bottom as a river does. In great lakes, such as those which drain into the St. Lawrence, storms develop a very heavy surf, and such lakes eat into their shores as the ocean does, but the very small tide confines the work of the waves within narrower limits, and the lighter breakers are less effective. Lakes are subject to various accidents which cause great fluctuations of the water-level. Deserted shore-lines are marked by beaches and terraces. The method of denudation by lakes is the same as that of the sea, but the modes of accumulation of material are characteristically different.

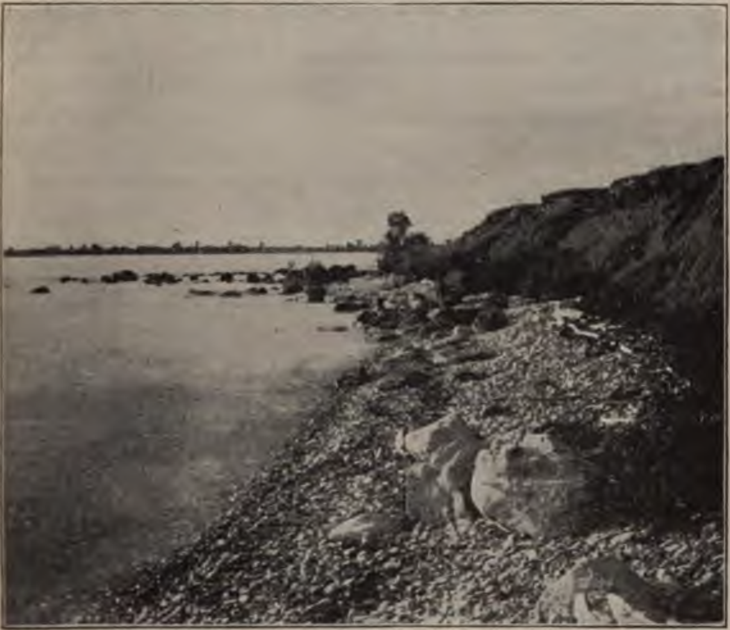

FIG. 45. — Beach on Lake Ontario. (U. S. G. S.)

ORGANIC AGENCIES

The organic agencies are animals and plants, both living and after death. In some respects these agencies tend to counteract the destructiveness of others, and the protective effects may be taken up first.

(1) *Protective Effects.* — The protective effects of organisms are almost entirely those of plants, since animals, on land at least, are not sufficiently abundant to be of any importance in this connection. A thick covering of vegetation, especially the elastic, matted roots of grassy turf, protects the soil against the mechanical wash of rain. How complete this protection often is, may be seen in the different effects produced by a heavy fall of rain upon a grass field and on the adjoining ploughed lands, or even on the roads. The roads may be so washed out as to be impassable, while the grass fields have not suffered at all. In certain of the western bad lands, the efficient protection given by grass is very well shown; where the grass has established itself thickly, the country is gently rolling, but where it is absent, the wild and broken bad lands are developed.

Vegetation, especially grass, protects loose, light soils from the wind, and often this is the only means by which sand dunes can be held in place and prevented from overwhelming valuable lands. Even the banks of rivers and the seacoast may be efficiently protected by plants. Dense masses of seaweed growing on the rocks form an elastic buffer against the surf, and along low-lying tropical coasts the mangrove trees, with their interlacing aërial roots, so break the force of the waves that they cannot wash away even fine mud.

The only protection afforded by animals that requires mention is in the case of coral reefs, which, thrown up along or parallel to the coast, shield it from the heaviest surf.

(2) *The Destructive Effects* of the organic agencies are decidedly subordinate to those of the other classes which have so far been considered, but they are not without importance. We have already learned how greatly the chemical activity of rain-water

is increased by the acids of vegetable decomposition, which it absorbs in its passage through the soil. Recent observations show that the decay of animals in the deep sea is an agent of no mean importance in promoting the chemical changes which there take place. But even living animals and plants play a part in the work of disintegrating rocks that should not be overlooked. Seeds germinating in the crevices of rocks, or the roots of trees which invade such crevices from above, wedge the rocks apart with the same irresistible power as is displayed by frost, and often large areas of rock are thus most effectively broken up. The roots of living plants also secrete an acid, which dissolves out some of the soluble constituents of rock, thus adding a chemical activity to the wedge-like mechanical effects of growth.

Many marine animals bore into rocks, even the hardest, and cause them to crumble, and on the land great numbers of animals continually bore and tunnel through the soil, allowing a freer access of air and water. In the tropics the soil is fairly alive with the multitude of burrowers. Earthworms are among the most important agents in work of this kind, and the last of Mr. Darwin's books was a most interesting one upon the geological work of worms. The worms swallow quantities of earth, for the sake of the organic matter which it contains, and grind it exceedingly fine in their muscular gizzards. This ground-up soil is always deposited on the surface, in the form of the coiled "worm-castings," so abundant in grassy places. Worms are thus continually undermining the soil, bringing up material from below and depositing it on the surface, while, by the collapse of the old burrows, the first surface gradually sinks. In England the material thus yearly brought to the surface varies from seven to eighteen tons per acre, which means an average annual addition of one-tenth to one-sixth of an inch. By this means the surface of the ground is constantly changed, and substances, spread over the ground, in the course of years make their way down into it, forming well-defined layers beneath the surface.

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CHAPTER VII

RECONSTRUCTIVE PROCESSES — LAND, SWAMP, AND RIVER DEPOSITS

We have now to inquire what becomes of the material derived from the mechanical and chemical disintegration of the rocks, for it is not destroyed, but only changed. Most of it is eventually carried to the sea and there deposited; but even on the land, and in lakes and rivers, a certain proportion of the waste finds a resting place for a longer or shorter period of time. While the rocks which form the accessible crust of the earth are, for the most part, of marine origin, yet those formed in other ways have great geological significance, because of the assistance that they give in the determination of ancient land surfaces, lake beds, river channels, ice fields, and the like. Hence it becomes necessary to study all the methods by which rock reconstruction is performed, on however small a scale.

I. Terrestrial Deposits

Under this head are included all those accumulations of the mechanical and chemical waste of preëxisting rocks, which are formed on land surfaces and not in bodies of water. Deposits made by ice, on land or under water, will be considered in a separate section.

Soil. — The crumbling remnant of disintegrated rocks forms soil, which under the influence of wind, rain, frost, and other agencies, is travelling down the slopes, accumulating, often to great thickness, in depressions and valleys. Very little soil, as such, is permanently built into the earth, by far the greater part of it reaching the sea and being sorted and deposited there. Sometimes, however, a soil-covered area is depressed beneath the sea or a lake, in such a way that the soil is not washed off, but new deposits are at once laid down upon its surface, and then the soil may be preserved for an indefinite period. Such an old soil, or "dirt bed," may be recognized by its texture and appearance and by the roots, stems, and leaves of land plants, with which it is apt to be filled. Old soils are also preserved in certain cases by lava flows, which have been poured out over them.

Talus and Breccias. — At the foot of cliffs and mountain slopes, great masses of talus, or angular blocks of all sizes, accumulate, chiefly through the action of frost. These masses form quite steep slopes and show an imperfect division into layers, and they are continually, but for the most part slowly, moving downward, through the action of the same forces that produced them. By the deposition of some cementing material (usually $CaCO_3$) the angular blocks may be consolidated into a solid mass, which is called *breccia*, and of which the peculiarity is that the fragments composing it are angular, not rounded.

Loess. — In arid regions the wind often carries the finer parts of the soil to immense distances and deposits it where it is less exposed to the wind, and where there is vegetation enough to hold it. In Central Asia the sun is often darkened for days by these dust-storms, and after they are past, a fine deposit of yellow dust is found over everything. Loess is a deposit formed in this way, and it is found in many lands. One of the largest known accumulations of it is in northern China, where it covers an immense area, to depths of 1000 to 1500 feet. It is not stratified, but cleaves vertically, and thus the ravines and valleys excavated in it have very abrupt sides. Loess also occurs in Europe, and the Pampas of the Argentine Republic are covered with a great thickness of it. The loess of the Mississippi valley is believed to have been laid down in water, under somewhat exceptional conditions.

Blown Sand. — Wherever a sandy soil occurs unprotected by vegetation, as in deserts or along the seacoast, the wind drifts the sand and piles it up into hills or sand dunes. The dunes are roughly divided into layers, the thickness and inclination of which

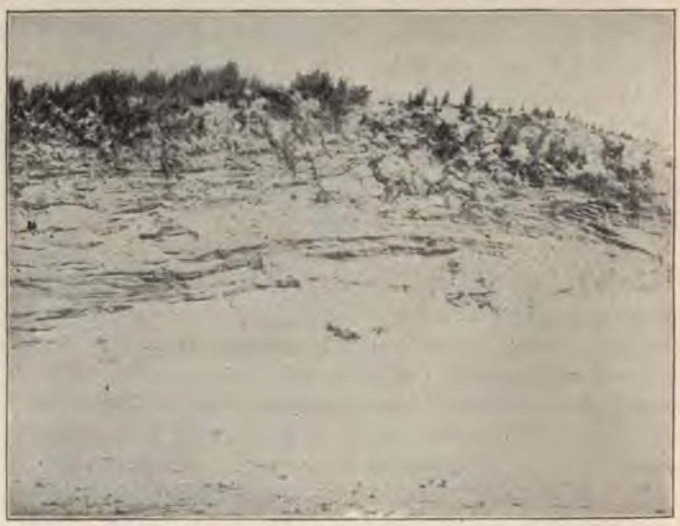


FIG. 46.—Sand dune on the coast of Rhode Island. (U. S. G. S.)

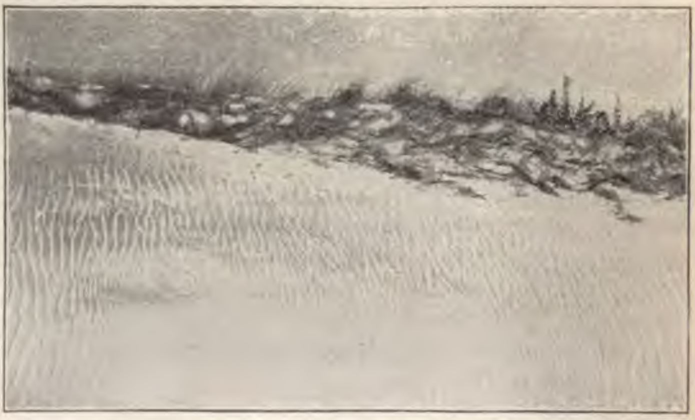


FIG. 47.—Sand dune, showing wind ripples. (U. S. G. S.)

depend upon the force and direction of the wind, and often imitate the confused arrangement of sands piled up by waves and currents under water. The sand-grains of the dunes are, however, more rounded by the abrasion which they have undergone, and, especially in deserts, they are apt to be smaller. When the sands are mixed with pieces of shells and other calcareous material, percolating waters, by dissolving and redepositing the $CaCO_3$, may cement the sands into firm rock. This is the more conspicuous when the whole material is calcareous, as in the shell sands of Bermuda. This substance, ground up by the surf, is transported inland by the wind and piled up into dunes. Rain-water cements the loose grains together, and by the alternate accumulation by wind and cementing by rain is formed the stratified æolian or drift-sand rock.

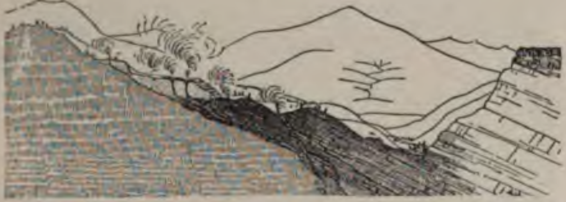


FIG. 48. — Ideal section through Mammoth Hot Springs, showing the water rising through limestone. (Hayden.)

Chemical Deposits. — As our knowledge of microscopic plants increases, many processes which were believed to be purely chemical, are found to be dependent upon the activity of minute plants. At present, it is not possible to distinguish accurately, in all cases, between the two kinds of processes.

Chemical deposits on the land are made principally by springs. Many springs precipitate carbonate of lime, on coming to the surface. The quantity of $CaCO_3$ which a given volume of water will dissolve, depends upon the amount of CO_2 contained in that water, and the quantity of dissolved gas, again, is determined by the pressure to which it is subjected. When the spring-waters reach the surface, the pressure is relieved, much of the CO_2 immediately escapes, and more or less of the $CaCO_3$ is deposited as *travertine* in the neighbourhood of the spring, often in masses of considerable extent and thickness. The process is not always entirely chemical. The beautiful calcareous terrace formed by the Mammoth Hot Springs, in the Yellowstone Park, is, in part at least, due to the separation of the lime salt from the water by a jelly-like plant, which grows in the hot water and is spread in bright coloured layers over the surface of the terrace. The parts of the terrace where deposition is no longer in progress, can be at once distinguished by their white colour.

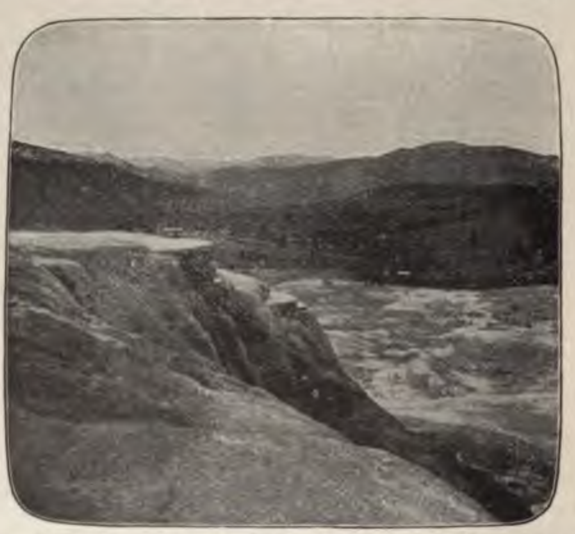


FIG. 49.—Travertine terrace of the Mammoth Hot Springs, Yellowstone Park.

Siliceous deposits are much less common than the calcareous, because of the rare conditions under which silica is dissolved in any considerable quantity, hot solutions of alkaline carbonates being necessary for this purpose. In the Yellowstone Park, especially on the Firehole River, are great terraces and flats of hard white siliceous sinter, or geyserite, which have been formed and are still being added to by the innumerable hot springs and

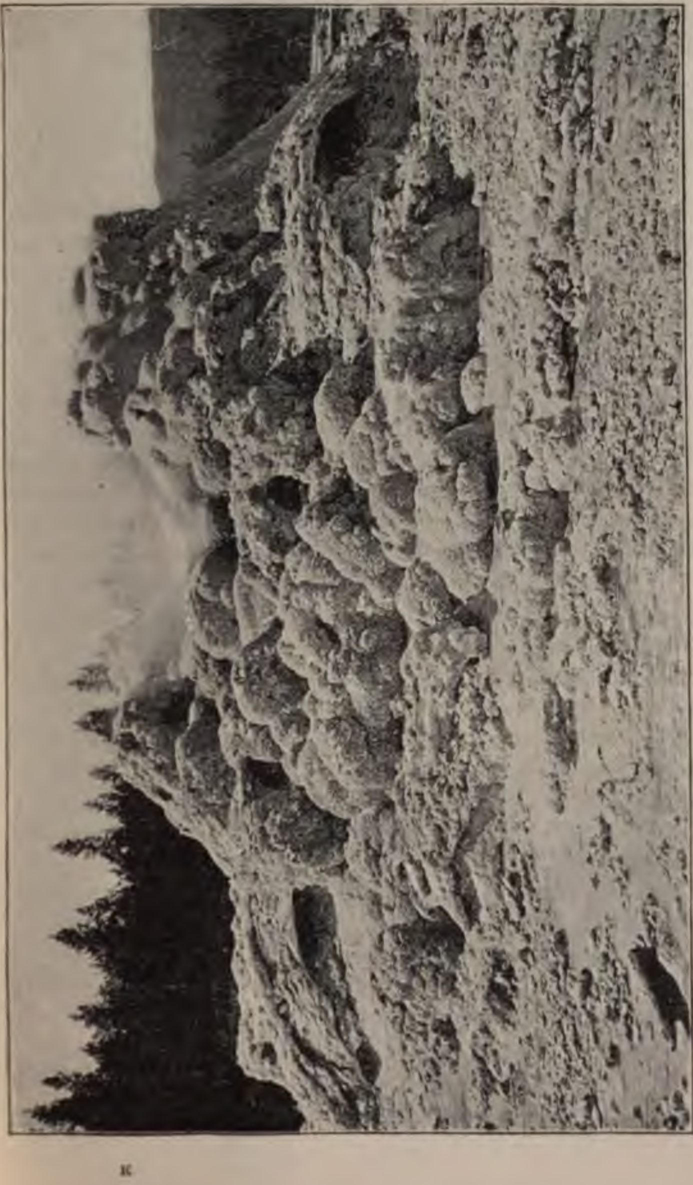


FIG. 50.—Crater of Castle Geyser, Yellowstone Park. The crater is composed of silica in the form of geyserite.

geysers. The silica is deposited partly by the evaporation of the water and partly by the action of *Algæ* (minute plants) which flourish in hot water pools. Similar deposits are found in the geyser regions of Iceland and New Zealand.

Iron deposits are formed by the springs known as *chalybeate*, which contain the carbonate of iron ($FeCO_3$) in solution. Contact with the air speedily converts the soluble carbonate into the insoluble F_2O_3, which forms brown stains and patches on the channels leading from such springs, and considerable quantities of it collect in pools. Here again, organic agency may supplement the chemical work, for certain diatoms extract iron from the water, as other Algæ extract lime and silica.

Certain mineral springs are of importance, as indicating the way in which mineral veins were formed. (See p. 265.) The Sulphur Bank Springs in the Coast Range of California are an especially instructive example of this activity. Below the depths to which the atmospheric influences penetrate, the fissures in the rocks are filled with hydrated silica, which is as soft as cheese and contains more or less cinnabar (sulphide of mercury). In other places the silica is hardened to chalcedony, and deposits of cinnabar mixed with iron pyrites fill up the crevices. The hot waters which build up these deposits are alkaline, charged with certain acids and alkaline sulphides. Near Virginia City, Nevada, hot alkaline springs rise through a series of fissures, in which they have deposited linings of silica, amorphous and chalcedonic, with some quartz, containing minute crystals of iron pyrites and traces of copper and gold. On the surface the springs have formed a thick layer of geyserite.

Phosphate Deposits are the only strictly terrestrial organic formations which require notice. These are principally derived from guano, which is the accumulated excrement of birds (in caves, of bats), and contains phosphates in large quantity. In rainless regions, such as the Peruvian coasts and islands, the guano may accumulate to great thickness without loss of its soluble matters, but in rainy districts these are largely carried away by percolating waters. Should the underlying rock be a limestone, it will be gradually converted from a carbonate into a phosphate of lime. Such is believed to be the mode of origin of the phosphatic rock of Florida and the West Indies. On the other hand, the phosphatic nodules of South Carolina are regarded as due to the action of swamp water upon underlying shell rocks, though the source of phosphoric acid is not well understood.

Cave Deposits. — The chemically formed cave deposits are due to the solution and redeposition of carbonate of lime. Caves are very generally found in limestones, and the percolating waters which make their way through the roof of a limestone cavern always have more or less $CaCO_3$ in solution. A drop of such water, hanging from the cavern roof, will lose some of its CO^2, upon the presence of which the solubility of the $CaCO_3$ depends, and deposit a little ring of the lime salt. Successive depositions will lengthen the ring to a tube, and then the tube will be built up by layers on the inner side, until it becomes a cone. At first, the deposit is white, opaque, and very friable, crumbling at a touch, but repeated depositions fill up the interstices of the porous mass and convert it into a hard, translucent stone, which assumes a crystalline structure through the development of calcite or aragonite crystals. The masses, thus formed, that depend from the roof of the cavern, are called *stalactites*. After hanging for a time from the roof, the drop of water falls to the floor of the cave, and there, in similar fashion, deposits a little layer of $CaCO_3$, which gradually grows upward into a cone. This is a *stalagmite*, and differs from the stalactite only in the fact that it grows upward from the floor, instead of downward from the roof. The stalagmite is, of course, exactly beneath the stalactite, and as long as the water continues to follow the same path, the two cones are steadily, though very slowly, increased both in height and thickness, until they meet, unite, and form a pillar extending from floor to roof of the cavern.

These deposits form the most curious and beautiful features of limestone caverns. The stalactites assume all manner of shapes, determined by the way in which the water trickles over them, and the abundance or scantiness of the water supply. Fantastic and beautiful shapes of every description, fringes of crystal spar, and curtain-like draperies hang from the roof and cover the walls of the chambers, while grotesque shapes rise from the floor, which is itself often a solid mass of the same deposit, and the pillars, once formed, are ornamented with every variety of fringe and sculpture. The constancy of the paths by which the water descends through the roof of the cavern, insures that the process shall continue uninterruptedly for very long periods of time. The Luray Caverns of Virginia are famous for the bizarre beauty of their formations, but limestone caves everywhere have more or less of the same deposit to show.

This process may be readily observed in any masonry arch, through which rain-water percolates, as a bridge, for example. The lime of the mortar is converted, in course of time, by contact with moist air, into $CaCO_3$, and this again is partially dissolved by the rain. When the rain-water trickles through the arch, it leaves icicle-like deposits, or thin sheets of calcareous matter, fringing the under side.

In a cave, it frequently happens that angular fragments fall from the roof and are cemented into a breccia by deposits of stalagmite. In caves connected with the surface by openings, sand and gravel, or fine soil and loam, are washed in by streams, or by the rain, and form the characteristic deposit known as *cave earth*. In ancient caverns, no longer subject to this wash, the whole deposit of earth may be sealed in by a covering of stalagmite. Cave earth has, in many instances, yielded great quantities of bones, which were washed in with the earth, or dragged in by the carnivorous animals which inhabited the cavern. The Port Kennedy cave in Pennsylvania is almost filled up by the bones of extinct animals which were washed into it, and many such cases are known, especially in Europe.

II. Palustrine or Swamp Deposits

The most important of the swamp and bog deposits are the vegetable accumulations, for the preservation of which a certain amount of water is necessary. The vast quantities of coal which occur in so many parts of the world, testify to the significance of the part which bog and swamp accumulations of vegetable matter have played in the earth's history. The nearest approach to coal that we have in process of formation at the present day, we find in the peat bogs, which are especially abundant and extensive in cool, damp climates, as in Ireland, Scandinavia, and the northern parts of North America. In northern regions the peat is formed principally by mosses, and especially by the bog moss, *Sphagnum;* elsewhere, as in the Great Dismal Swamp of Virginia, the leaves of trees and various aquatic plants are the sources of supply.

Vegetable matter consists of carbon, hydrogen, oxygen, and nitrogen, with a certain proportion of mineral matter, or ash. When decaying on the ground, exposed to the air, the plant tissues are completely oxidized, and form such simple and stable compounds as CO_2, H_2O, NH_3, and the more complex humous acids, and thus hardly any solid residue is left. In forests the accumulation of leaves for many centuries results only in a shallow layer of vegetable mould. Under water, where the supply of oxygen is very limited, vegetable decomposition is much less complete. Some CO_2, H_2O, and CH_4 (marsh gas) are formed, but much of the hydrogen and nearly all of the carbon remain; the farther decomposition proceeds, the higher does the percentage of carbon rise, and the darker does the colour of the mass become. Peat frequently forms in small lakes and ponds, aquatic plants growing out from the edges and on the surface, until they gradually fill up the basin and convert the pond into a bog.

The Great Dismal Swamp of Virginia and North Carolina probably more nearly reproduces than do most existing peat bogs the conditions of the ancient coal swamps. The swamp, which measures thirty miles by ten, is a dense growth of vegetation upon a water-covered soil of pure peat about fifteen feet deep and with no admixture of sediment. The swamp cypress grows abundantly in the bog, and prevents, by its dense shade, the evaporation which would take place in summer, could the sun's rays penetrate to the wet soil. The shallow layer of water which covers the ground receives the fallen leaves, twigs, and branches, and sometimes even the trunks of fallen trees, preventing their complete decomposition, while the dense covering of mosses, reeds, and ferns which carpet the ground, add their quota to the mass of decaying vegetable matter. At the bottom of the bog, it is of interest to observe, is a layer of fire-clay, which, by its imperviousness, tends to hold the water and prevent its draining away. Peat swamps, formed in a similar manner, also occur at the mouths of great rivers, such as the Mississippi.

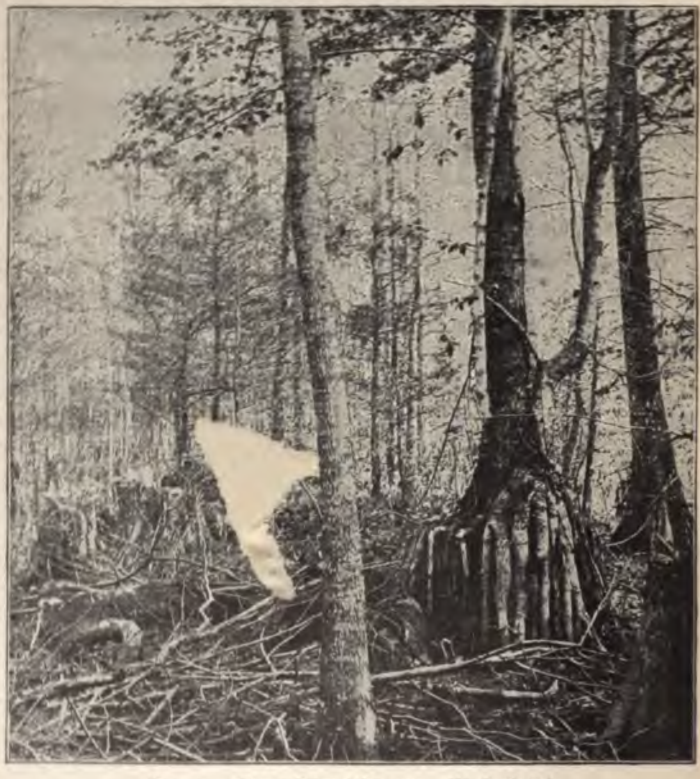


FIG. 51.—Great Dismal Swamp. (U. S. G. S.)

The bogs of northern latitudes are due principally to the bog moss *Sphagnum*, which forms dense and tangled masses of vegetation, dead and decaying below, green and flourishing above. As these mosses hold water like a sponge, they will develop bogs in any shallow depression, or even on a flat surface, where they may get a foothold. The depth of peat is sometimes as much as fifty feet, and its density and fineness of grain increase with the depth and the length of time it has been macerating in water.

Fire-clay is frequently found at the bottom of peat bogs, and is directly connected with the processes of vegetable decomposition, though not itself of organic origin. Fire-clay contains a large admixture of siliceous sand, but is free from lime, magnesia, the alkalies, and any high percentage of iron; it is thus a mixture of nearly pure clay and sand, which may be heated very highly without melting or crumbling. The iron, alkalies, and alkaline earths are gradually leached out of the clay by the action of the peaty water, which is charged with humous acids, and thus an ordinary clay is converted into a fire-clay. Fire-clay occurs frequently beneath coal seams; as the percentage of [illegible] becomes very high, fire-clay passes over into *gannister*, [illegible] largely used for the lining of iron furnaces.

Bog Iron-ore is another substance which is indirectly due to the decay of plants; it is found at the bottom of bogs, or lakes, in deposits which are sometimes many feet thick. Iron is a very widely disseminated substance, occurring in almost all rocks and soils, though usually in very small quantities. Immediately at or very near the surface of the ground the ordinary iron ingredient is the red oxide Fe_2O_3, an exceedingly stable compound. In contact with decomposing organic matter, and protected from the air, Fe_2O_3 is deoxidized and converted into FeO ($Fe_2O_3 - O = Fe_2O_2 = FeO$); this in its turn takes up CO_2, which is present in all such waters, and becomes $FeCO_3$, which is soluble in carbonated water. Solutions of $FeCO_3$ accumulate under peat bogs and deposit their mineral by concentration; but when the iron-bearing waters evaporate in contact with the air, the carbonate is reconverted into the red oxide, by the loss of CO_2 and absorption of O.

III. Fluviatile or River Deposits

In a preceding chapter we learned that the power of a stream of water to transport sediment depends upon its velocity, which, in its turn, is determined by the slope of the ground and the volume of water. Further, we discovered the very surprising fact that the transporting power increases as the sixth power of the velocity ($T = V^6$). It follows from this that a slight decrease in the swiftness of a stream will cause it to throw down the greater part of its load of sediment, while a slight increase will cause it to carry off what it had before deposited. Thus, great rivers, like the Mississippi, which flow in soft, easily moved deposits, are preëminently whimsical and treacherous. As the volume and velocity of the stream are much subject to change, there will obviously be corresponding changes in the scour and deposition at any given point, but there are certain places where deposition is so constant that extensive accumulations may be formed there. As we trace a river downward from its source in a mountain region, we find that in the upper stream, which is a torrent in swiftness, only large stones remain at rest, everything else being swept along. Farther down stream, as the slope of the bed diminishes, the coarse gravel is thrown down, next the coarse sand is deposited, and in the lower reaches of a river, which, like the Mississippi, flows over land that has a very gentle slope, and is raised but little above the sea-level, only the finest silt gathers on the bottom. The exact limits of the different kinds of deposit will vary with the stage of water.

At points where the velocity of the stream meets a constant check, there will be constant deposition, and thus bars and islands are built up in the channel, which will be permanent unless some change of conditions is brought about. In the gravel and sand banks the material is *stratified*, or divided more or less distinctly into layers made up of similar fragments, each layer representing uninterrupted deposition. A pause in deposition will produce a division plane, which is, of course, all the more marked if the deposited material be changed after the pause. In the sand bars and gravel spits the up-stream side is a gentle slope, ending abruptly on the down-stream side, the bar or spit advancing by having sand or gravel pushed up the gentle slope by the current and dropped over the steep face, where it forms inclined layers. Flattened and elongated pebbles arrange themselves so as to offer the least resistance to the current, in a slanting position, with their tops down stream. When the stream is subsiding, the material tends to assume a more horizontal direction, giving an irregular and confused stratification to these deposits.

Alluvial Cones or Fans. — Where a swift torrent, descending a steep slope, debouches on a plain or wide valley, its velocity is greatly diminished, and a large part of the material which it carries is thrown down and spread in a fan shape from the opening of the ravine in which the torrent flows. The thickness of the cone is greatest at the mouth of the ravine, while its breadth increases outward from that point. Where several such torrents open on the plain near together, their fans may coalesce and form a continuous fringe along the base of the mountain. The slope of the cone's surface diminishes with the size of the stream; in small streams it may be as steep as 10°. These cones are formed on much the same principle as deltas, and might, with propriety, be called terrestrial deltas. Very large alluvial cones are found in the Rocky Mountain and Great Basin regions. (See Fig. 52.)

Flood Plains. — Rivers, as is well known, are subject to floods, when the volume of water is enormously increased and can no longer be contained in the ordinary channel, but spreads out over the level ground on each side. By this spreading, which may be for many miles in both directions, the velocity of the water is much diminished, and over the flooded area (flood plain) large quantities of material are thrown down, while the unchecked velocity in the channel will cause a scouring and deepening there. The nature of the material deposited over the flood plain will depend on the character and swiftness of the flooded stream, and varies from the coarsest gravel to the finest silt. The latter is more usual, for the flood plain is widest along the lower course of the river. A line of maximum deposition occurs where the swift current of the channel is retarded by contact with the sluggish waters

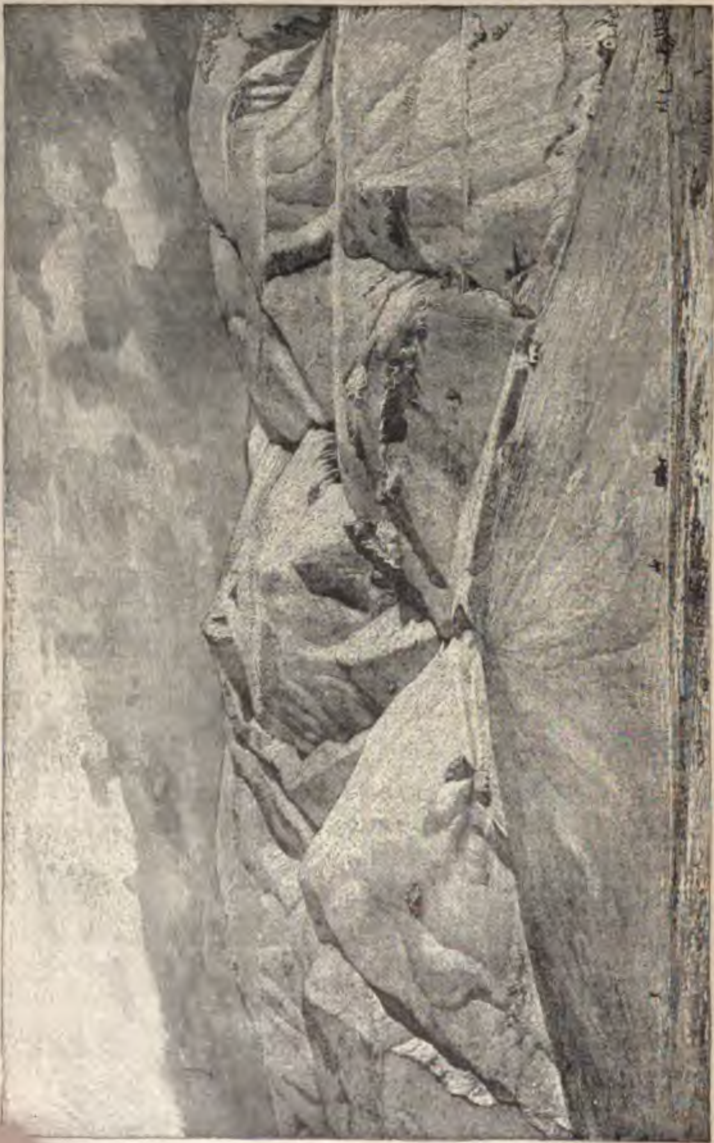


FIG. 52.—Alluvial cone. Wasatch Mountains, Utah. (Gilbert.)

of the flood plain, and thus the surface of the plain slopes away from the river. Along the lower Mississippi this slope is as much as seven feet for the first mile. The vegetation, grass, bushes, and trees, which grows over the flood plain, acts as a sieve and catches the sediment, so that little escapes. Lands thus annually renewed by a deposit of river mud are of wonderful fertility, and, like Egypt, for example, remain so after thousands of years of cultivation. In this manner the flood plain is slowly raised, while, at the same time, the channel is deepened, and by the river's double activity of scour and deposition, certain very characteristic features result.

River Terraces and Old Gravels. — The lower courses of many rivers, including most of those in the northern United States, and some in the southern, are bordered by a succession of terraces that rise symmetrically on the two sides of the stream. Sometimes, as in many English rivers, the terraces are at different levels on opposite sides. The formation of these terraces is due to the twofold activity of the river already described. The combined deepening of the channel and building up of the flood plain at length make the trough of the river so deep that floods no longer fill it, especially if the velocity of the current be maintained or increased by an elevation of the region drained by the river. Then the energy of the current is partly employed in widening the channel and forming a new flood plain, cutting back the edges of the old flood plain, which it can no longer overflow, thus converting it into a terrace, which is the remnant of an old flood plain. The process may be repeated many times, and thus successive terraces rise, one above another, as we recede from the river.

It necessarily follows from this account that the highest terrace is the oldest, and the lowest is the last formed. This seems to be a violation of the rule that, in any series of sedimentary deposits, the oldest must be at the bottom and the newest at the top; but the violation is only apparent, not real. Were the river to flow at a constant level, no terraces could be formed, and the deposits would follow the rule, just as they do now in each successive flood plain and terrace. Because, however, the stream flows at successively lower levels, the lower flood plain is made up of the newer deposits. It should further be observed that the older gravels do not actually overlie the newer ones, but are merely at higher levels.

Unsymmetrical terraces, which are either confined to one side of the river, or if present on both sides, are on different levels, are formed when a stream is widening its valley by steadily cutting away the bank on one side, shifting the channel toward that side, and at the same time deepening it. This will result in the formation of terraces representing the former positions of the stream. If the lateral movement be all in one direction, the terraces will all be on the side away from which the channel is shifting; if it be alternately in opposite directions, terraces will be formed on both sides, but at different levels.

Still a third method of terrace formation should be mentioned. If a river which has excavated a deep valley, have its velocity checked by a slow subsidence of the country, it will commence to fill up its valley with gravel or other sediment, and may thus accumulate material of great thickness and extent. Should a re-elevation of the country now occur, the river will acquire new destructive power and cut a terraced channel down through its own deposits. In such a case the material is a continuous mass, and the gravels of the higher terraces are newer (not older) than those of the lower. The rivers Mersey and Irwell in England are believed to be examples of this mode of terrace formation.

Deltas are accumulations of river deposits at the mouths of streams, land areas which the rivers have recovered from the body of water into which they flow. The factors which determine the formation of a delta are not altogether clear. The presence or absence of a strong tide is evidently one of these factors, for in lakes and in seas with little or no tide, almost all streams form deltas, while those rivers which empty into the open ocean almost invariably do so by means of estuaries, in which the sea encroaches on the land. In North America the rivers which discharge into the Gulf of Mexico form deltas, while the Atlantic streams nearly all have estuaries. In Europe the delta-forming rivers empty into the Mediterranean, the Baltic, and the Black and Caspian seas.

Nevertheless, the tide is evidently not the sole factor in determining the presence of a delta; the Thames and the Rhine discharge into opposite sides of the North Sea, yet, while the latter has built up a delta, the former opens into a wide estuary. If the sea-bottom is subsiding faster than the river deposit is built up, no delta will be formed, but an estuary. The Ganges and Brahmapootra have formed a vast delta in spite of the powerful tide of the Bay of Bengal.

When a stream loaded with sediment flows into the relatively stationary waters of a lake or sea, its velocity is checked and the greater part of its load very rapidly thrown down. Deposition takes place much more rapidly in salt water than in fresh, because the dissolved salts reduce the cohesion of the water, and hence diminish the friction which retards the settling of silt. The excessively fine particles of clay, which in fresh water remain suspended for weeks, are thrown down in salt water in a few hours; hence the great mass of the sediment falls to the bottom in the vicinity of the stream's mouth. Such rapid accumulation obstructs the flow of the river and causes it to divide and seek new channels, especially in time of flood, and form a network of sluggish streams meandering across the low flats. The height of the delta is increased by the spreading waters of the river, when in flood, and the growth of vegetation assists in raising the land. Though the Mississippi delta is an area of subsidence, two-thirds of its surface are above water, when the river is in its ordinary stages. But for the levees, however, most of it would be inundated in times of flood.

The nature of the materials of which deltas consist varies according to circumstances. When mountains are near the coast, the streams flowing from them may descend into the sea with sufficient velocity to build a delta of cobblestones and coarse gravel. Usually, however, deltas formed in seas are composed of very fine materials, because the lower course of most rivers is through flat plains, and the stream can only carry very fine silt. Even in such cases, there will be differences in the coarseness and fineness of the material, corresponding to the seasons of high and low water in the river.

The rate of delta growth is dependent upon the quantity of sediment which the river brings down, the depth of water to be filled, the force of tides and currents which scatter the materials, and the rate of subsidence of the sea-bottom, should subsidence occur. At the present rate the Mississippi is pushing its delta into the Gulf one mile for every sixteen years. The delta of the Rhone has advanced into the Mediterranean more than fourteen miles since the beginning of our era, while that of the upper Rhone in Lake Geneva has been built out one and one-half miles in the same time. The Po delta in the Adriatic has added twenty miles to the land since the time of Augustus, and the town of Adria, then a seaport, is now that distance from the shore. In fact, the whole Adriatic coast, from Trieste to Ravenna, is a delta formation, which has widened from two to twenty miles since Roman times. The Nile delta, on the other hand, has advanced very little in the same period, for a strong current sweeps along its sea front and carries away the sediment.

The combined delta of the Ganges and Brahmapootra, the two largest rivers of India, is interesting as an example of a delta built up against a strong tide. The area of this delta is given as 50,000 square miles, and it is still advancing, the rivers depositing more sediment in flood time than the sea can remove in the dry season. The enormous quantity of material carried by the Ganges and Brahmapootra, which far exceeds that of the Mississippi, is probably the most important factor which determines the formation of the delta, despite the scouring action of the sea. The great rivers of China, the Hoang-ho and the Yang-tze-kiang, which probably transport more solid matters than any other stream except the Amazon, have formed an immense delta plain around the head of the Yellow Sea, which owes its colour to the mud of these streams.

CHAPTER VIII

RECONSTRUCTIVE PROCESSES — LAKE AND ICE DEPOSITS

IV. Lacustrine or Lake Deposits

Lakes are important places of sedimentary accumulation, for the streams that flow into them deposit all their loads of suspended material, and however turbid the inflowing streams, the outlet is clear and sparkling, the lake acting as a settling basin. A most striking instance of this is the Rhone, which enters Lake Geneva a muddy, glacial torrent, but flows out in a state of exquisite purity. The Niagara, as it leaves Lake Erie, is likewise beautifully clear. Occasional exceptions to this rule may occur, as when a shore current of the lake washes sediment into the outlet, but for the most part, the lake intercepts and holds all the sediments carried by its tributary streams.

1. **Fresh-water Lakes.** *a. Mechanical Deposits.* — The mechanical sediment which accumulates in a lake basin is of two kinds, (1) that which is brought in by tributary streams, and (2) that which the lake itself acquires by cutting into its shores. In most cases the stream-borne sediment is much the more important of the two classes. The rivers which empty into lakes nearly all form deltas; if a strong shore current sweeps past the mouth of the stream, it will distribute part of the materials along the shore, and the waves will act as transporting agents to the same effect. The deltas spread out in a fan-shape from the mouths of the inflowing streams, and if they are numerous enough, may surround the entire lake with delta deposits. In each delta the successive layers of sediment will have an inclination dependent upon the depth of water into which the stream debouches and the coarseness of the débris carried. If in deep water, the beds may

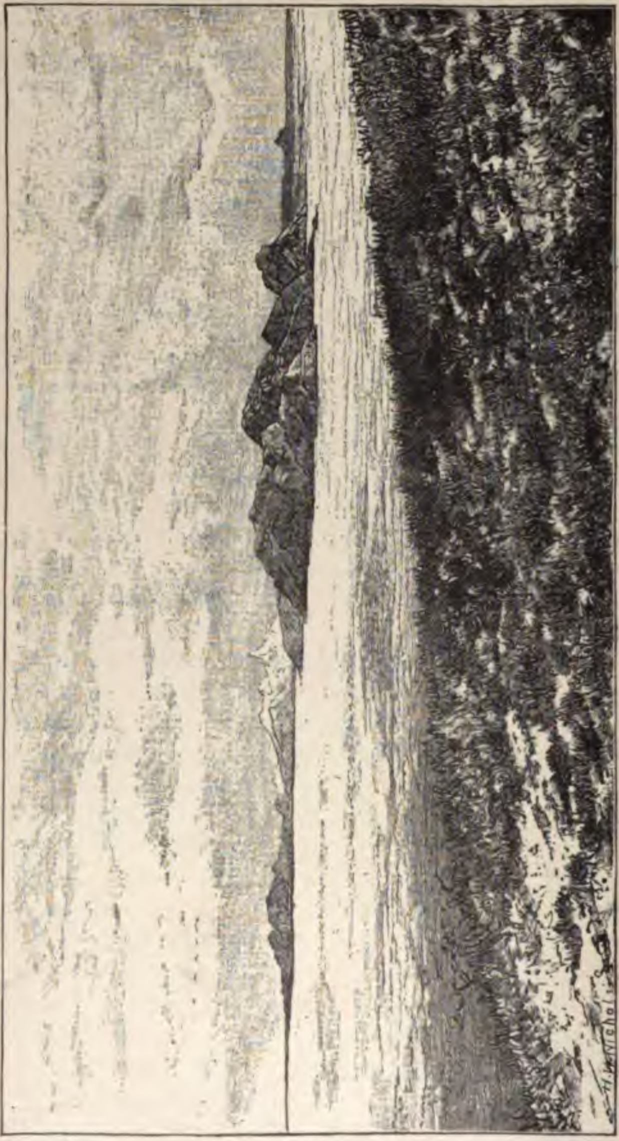


FIG. 53.— Mountains nearly buried under old lake deposits; plain of Salt Lake, Utah. (Gilbert.)

be inclined at a considerable angle; if in shallow water, they form a very gradual slope. In small lakes the coalescence of deltas, or the advance of a single one, will eventually fill up the basin, forming first swamps and then smooth, grassy meadows, through which flow the streams, keeping their own channels clear. Such filled-up lakes are common in many mountain ranges. In large lakes the process is, of course, much slower, and the lake is apt to be drained by geographical or climatic changes, long before the basin is choked with sediment.

Away from the deltas the combined action of the waves and currents fringes the lake with coarse deposits of boulders, gravel, and sand, which form the beach, the sand extending some distance out into shallow water. The finer materials are carried out into deeper water and deposited in successive layers over the whole lake bottom, the finest materials in the centre. The coarse and fine sediments grade into each other, dovetail and overlap, because in heavy storms or when the streams are in flood, the coarser sediments are carried farther out and deposited on the fine, and these changes of material in any given vertical section, not too far from shore, may be often repeated. Special lines of accumulation for the coarse substances also occur in the form of shoals, spits, embankments, and the like. If the lake is subject to fluctuations of its level, with the water much higher at one time than another, even more wide-spread changes in the character of the deposits will occur. The deposits now forming in the great Laurentian lakes are principally blue muds and clays, partly made up of kaolinite and partly of the débris of other minerals, in an extremely fine state of subdivision, but not decomposed chemically. In Lake Superior the clay has generally a pinkish tinge.

Stratification. — It has been incidentally remarked that the sediment accumulated in lakes is divided into layers, which, except locally, are laid down in a horizontal position. This division into layers is *stratification,* and the sediment is said to be *stratified.* Not that stratification is peculiar to lake deposits; on the contrary, it is characteristic of all accumulations made under water. It is due to the *sorting power* of water, by which, so long as conditions remain the same, particles of similar size and weight are thrown down at the same spot. If sand, gravel, mud, and clay be shaken in a jar of water and then allowed to stand, the various materials will settle to the bottom in the order of their coarseness, the finest coming down last. Yet, in this case, the change from one kind of material to another will be so gradual, that no well-defined layers will appear, to produce which deposition must cease at intervals, or the kind of material be changed. Each layer represents a time of deposition followed by a pause, which allows the surface particles to assume a somewhat different arrangement from what they otherwise would do. The planes of contact between the successive layers are called the *bedding* or *stratification planes*, and it is along these that the mass of sediment most readily parts. The sorting power of the water in a lake thus causes the coarser materials to be thrown down near shore, and the finer to be carried farther out, but changes in the transporting power, caused by storms, high water, and the like, change the place of deposition for particles of a given size, and thus pile gravel on sand, and sand on mud, or *vice versa*.

Owing to the way in which the materials are arranged, lake deposits betray the form of the basin in which they were laid down. Around the old shore line are masses of coarse materials, with deltas interspersed, to mark the mouths of streams, while towards the middle of the basin, quantities of fine mud and clay have accumulated. An excellent example of such a deserted lake basin is that known as Lake Bonneville in Utah, of which Salt Lake is the shrunken remnant. The drying up of this lake, which was once fresh and had an outlet northward to the Snake River, is an event geologically so recent, that its form and size, its shores and islands, its high and low stages, in short, its history, can be made out with great clearness, as has been admirably done by Mr. Gilbert of the United States Geological Survey. At its time of greatest extension, Lake Bonneville had an area of 19,750 square miles and a maximum depth of 1050 feet, while Salt Lake (which is variable) had in 1869 an area of 2170 miles and an extreme depth of 46 feet. Around the ancient shores are beauti-

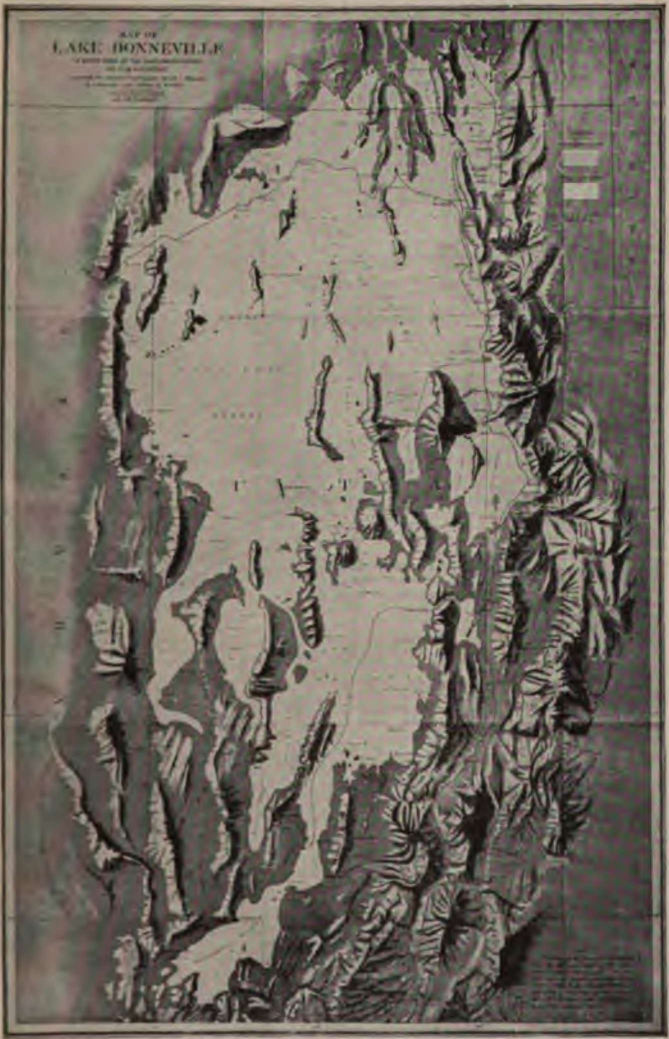


FIG. 54. — Map of Lake Bonneville. The pale area near the upper end marks the present outline of Great Salt Lake. (Gilbert.)

fully preserved the terraces, embankments, and deltas of the various stages of water, with the gravels and sands appropriate to the shallow water. The principal part of the basin is a level plain, filled to a great but unknown depth with beds of clay and marl. (Fig. 53.)

In still more ancient lakes the terraces, embankments, and other shore features have been swept away by the processes of denudation, but the outline of the lake may frequently be reconstructed from the character of the deposits.

b. Chemical Deposits are not common, nor of much importance in fresh lakes. In a few, chemically precipitated carbonate of lime is found, and more abundant is limonite (Fe_2O_3, H_2O). This is carried into the lake by streams that contain dissolved ferrous carbonate ($FeCO_3$), which, becoming oxidized and hydrated, is no longer soluble, and accumulates on the bottom. In Sweden ores of this kind are dredged out of the lakes and employed as a source of iron.

c. Organic Deposits are seldom important in large lakes, but often decidedly so in small ones. As we have already seen, peat often forms to such an extent as to choke up the lake and convert it into a bog. Siliceous accumulations are made on an extensive scale by the minute plants, *diatoms*, which though of microscopic size, yet multiply with extraordinary rapidity; their tests of transparent flint gather on many lake bottoms in a fine deposit, as white as flour, and variously called Tripoli, or polishing powder, or infusorial earth. Calcareous accumulations are formed by the shells of fresh-water molluscs, often in masses of considerable thickness. The lower layers of this *shell marl* have generally been so much disintegrated by the water as to be without any obvious organic structure. Such marls are frequently found under peat bogs and indicate that the latter were originally lakes, and in the marl often occur the bones of extinct animals.

2. Salt Lakes are especially characteristic of arid climates in which the rainfall is light and evaporation great. They may be formed either through the separation of bodies of water from the sea, or by the long-continued concentration of river water in basins that have no outlet, where the influx of water is disposed of by evaporation from the surface of the lake. In either case an arid climate is requisite to maintain the salinity; in a moist region the large rainfall and slower evaporation would cause the lake to rise until it found an outlet, and then the water, if originally salt, would become fresh. The history of Lake Bonneville exemplifies the change from fresh to saline conditions. As long as the water level was maintained above the outlet, the lake was fresh, but when the advancing aridity of the climate diminished the rainfall and increased the rate of evaporation, the water level sank until it fell below the outlet. Then the lake became saline, reaching its maximum salinity in the intensely bitter waters of Salt Lake, which is the remnant of the large lake.

All river water contains greater or less quantities of dissolved matters, and of these one of the commonest is ordinary salt ($NaCl$). When such waters are evaporated, the solids remain behind, and thus the water becomes more and more saline till it reaches saturation. Other substances occur also, as will be seen below.

The mechanical deposits formed in salt lakes do not differ in any very important manner from those of fresh lakes. The finer clays settle more rapidly in brine than in fresh water, which makes strongly saline lakes extraordinarily clear and limpid. The organic deposits of salt lakes are practically nothing, for brackish water is not favourable to many organisms and in dense brines very few animals or plants can exist, and those that can are not the kinds which give rise to peat, or to siliceous or calcareous deposits. For the same reason, the deposits of whatever kind, laid down in salt lakes, are almost barren of fossils, except of land animals and plants, such as are washed into the lake by flooded streams.

The *chemical deposits* are much the most interesting and characteristic of the accumulations gathered in salt lakes. These chemical precipitates differ much in the various lakes, according to the nature of the rocks which form the drainage basins, but while some of the substances are rare and restricted in extent, others are extremely common and wide-spread. Several changing factors combine to vary the order of precipitation of the salts in different lakes, but, in general, it follows the inverse order of solubility, the least soluble material being deposited first and the most soluble last. Comparatively little chemical reaction appears to take place in these lakes; the substances are, for the most part, thrown down merely by the evaporation of saturated solutions and are the same as those carried in very dilute solutions by the tributary springs and streams. If the precipitation of salts is slow and occasional, the chemically and mechanically formed deposits are mingled together; but if such precipitation be rapid, then thick and nearly pure masses of the salts are thrown down in their proper order, as the concentration by evaporation proceeds.

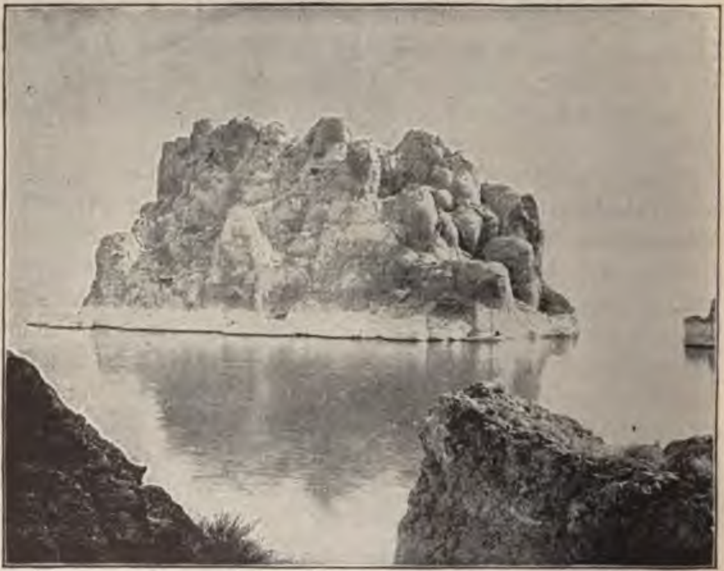


FIG. 55.—Island of calcareous tufa, Pyramid Lake, Nevada. (U. S. G. S.)

The first substances to be deposited from solution are the carbonate of lime and red oxide of iron ($CaCO_3$ and Fe_2O_3), and in moderately saline lakes this is about the limit of precipitation. These same materials are thrown down in fresh lakes also, and their deposition is principally due to the loss of the solvent CO_2. The ancient Lake Lahontan, which formerly occupied part of northwestern Nevada, was the seat of calcareous deposition on a magnificent scale, and every crag and island which its waters touched is sheathed in thick masses of calcareous sinter. Pyramid Lake, a remnant of Lahontan, has a remarkable island of calcareous tufa; and Mono Lake, California, is famous for similar deposits, which have assumed curious and whimsical shapes.

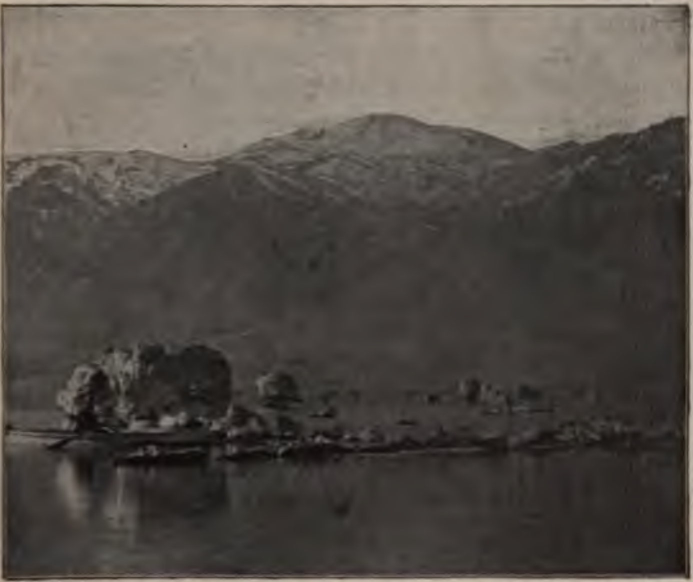


FIG. 56.—Calcareous deposits in Mono Lake, California. (U. S. G. S.)

As the concentration of the lake waters proceeds, the next substance to be precipitated is gypsum ($CaSO_4$, $2\,H_2O$), which, though much more soluble than the carbonate of lime, is yet only sparingly so. After all the gypsum in solution has been thrown down, there follows a pause in the deposition, until a further stage of concentration has been reached, and then common salt is precipitated, which deposition continues steadily as concentration proceeds, but at an advanced stage the salt is mingled with the sulphate of magnesia ($MgSO_4$), should that be present. The highly soluble salts, such as the chlorides of magnesium and calcium (MgCl, CaCl), remain in solution until the water is completely evaporated to dryness, hence they are rarely found in beds of rock salt.

Various circumstances may change the order of precipitation just given. In seasons of high water the flooded rivers dilute the waters of the lake, checking the chemical precipitation and, at the same time, increasing the mechanical deposition; thus beds of sand and mud are thrown down upon the beds of gypsum and salt, alternating with them, as the influx of fresh water or evaporation predominates. Changes of temperature also have an effect upon the order of precipitation. Thus, in cold weather, Salt Lake washes up on its shores quantities of sulphate of soda (Na_2SO_4), which is formed at low temperatures by the double decomposition of NaCl and $MgSO_4$.

Besides the chemical deposits already mentioned, others occur on a smaller scale. On the western side of the Great Basin, in Nevada, California, and Oregon, are several lakes which contain large proportions of carbonate of soda, and in some of them the concentration is sufficiently advanced to cause precipitation.

Much the most abundant of the chemical deposits made in salt lakes are gypsum and rock salt, and the enormous scale on which the latter was formed in past ages of the world's history is demonstrated by the vast bodies of rock salt which are found embedded in the rocks in so many parts of the world. Near Berlin, at Sperenberg, an artesian well was sunk through such a deposit for nearly 4000 feet, without reaching the bottom. In various regions of the United States, notably in New York and Kansas, large bodies of salt are found, but not on such a scale as in Europe.

It should be noted that the chemical deposits made in salt lakes are crystalline and at the same time stratified. This association is not the usual one, as stratified rocks are ordinarily not crystalline, and crystalline rocks are mostly unstratified.

V. ICE DEPOSITS

Deposits made, directly or indirectly, by the agency of ice are very characteristic, and though some are formed on land and some under water, it is desirable to consider them together in a single section. The peculiar features of ice formations may be much obscured by the action of water, either at the time of their deposition or at some subsequent period. Ice deposits play but a very small part in the construction of the earth's crust, but the light which they throw upon changes of climate and similar questions, lends them an unusual degree of interest.

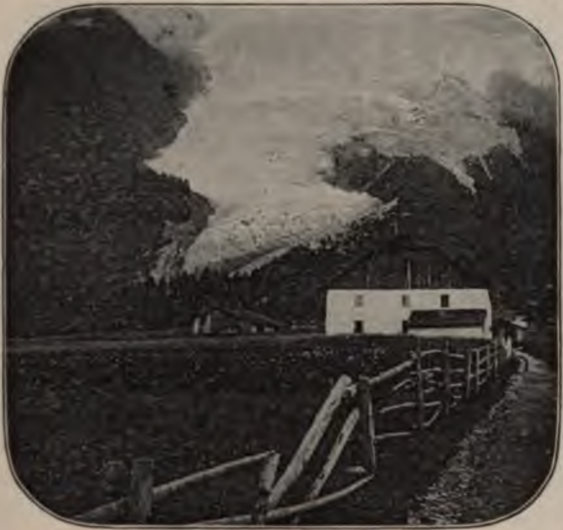


FIG. 57.—Glacier des Bossons, Switzerland. The terminal moraine follows the lower end of the glacier. (Photograph by McAllister.)

Glacial Deposits.—We have already learned that glaciers carry with them great masses of débris, either in the form of lateral and medial moraines upon their upper surfaces, or frozen in the interior of the ice, or pushed along beneath it. When the glacier arrives at its lower end, where the rates of motion and melting balance each other, all the burden which it is transporting is deposited in a great mound or ridge, the *terminal moraine*. Moving ice does not sort the material which it carries, as flowing water does, because in a glacier there is no such definite relation between velocity and transporting power. Hence, the terminal moraine is unstratified and is composed of materials of all sizes, from dust and sand up to great boulders weighing hundreds of tons, all mingled together in confusion. In the case of a glacier which carries the principal part of its burden upon its upper surface, the terminal moraine is chiefly made up of angular blocks that have undergone little or no abrasion, together with earth, sand, gravel, and whatever kind of material the overhanging cliffs may have delivered to the moving ice. Mingled with these materials, however, will be found more or fewer of the characteristically worn and grooved glacial pebbles and boulders, which have been dragged along under the ice, and scored and polished by the rocky bed. There will also be found some, at least, of the sand and fine rock flour which the glacier's own movement

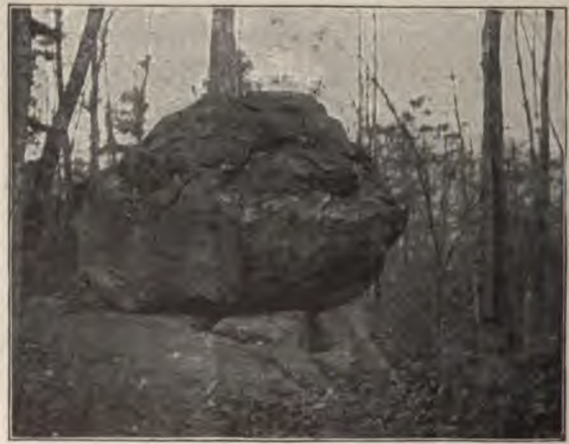


FIG. 58.—Perched block of sandstone resting on trap, Palisade Ridge, N.J. (Photograph by Salisbury.)

produces and which have escaped the washing of the sub-glacial stream.

When a glacier is retreating, it may build up a new terminal moraine at each point of arrested withdrawal, or if the retreat is gradual and steady, the ground in front of the ice will be covered with moraine material, spread out in a sheet, not heaped up in a moraine or mound. The retreat of the glacier may leave behind it isolated masses of ice deeply buried in the débris of the terminal moraine; when such masses melt they form depressions in the mound and give rise to the "kettle moraines." A shrinking glacier will contract laterally and in depth, as well as longitudinally, and in this way the blocks of the lateral moraine will be left stranded at intervals over the former glacial bed. Such blocks and boulders are known as *erratics*, or perched blocks, and when their parent

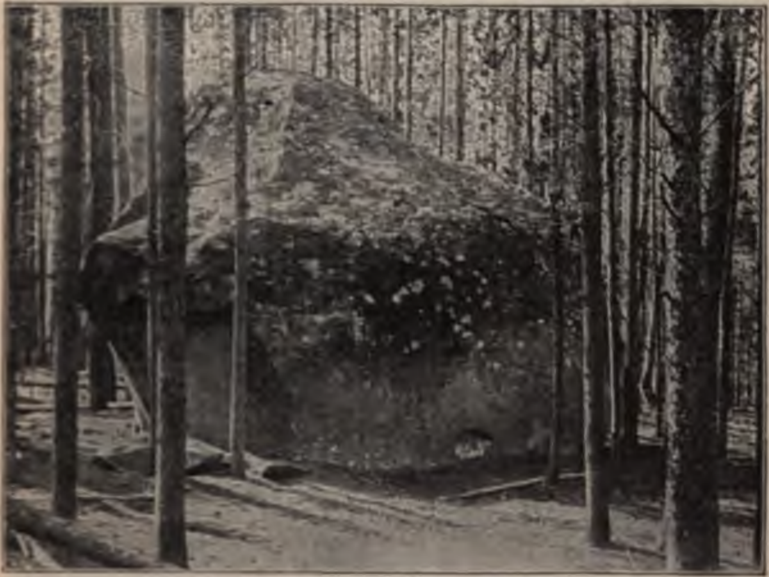


FIG. 59.—Perched block near the Yellowstone Cañon, National Park. (U. S. G. S.)

ledge can be discovered, it is easy to determine the distance to which they have been carried. Sometimes a great boulder is lowered so gradually and gently by the retreating ice, that it is exactly balanced, and may be moved backward and forward by the hand. This is a "rocking-stone," though it must not be supposed that all rocking-stones are glacial. (See p. 86.)

The water deposits which are made in the neighbourhood of and in association with a glacier, are also characteristic and should be noticed in this connection. Very instructive examples of this combined action may be observed about the great Malaspina glacier in Alaska. This is an immense ice-sheet, with an area of 1500 square miles, which is formed at the foot of the St. Elias Alps by the confluence of several great glaciers. All the outer borders of the glacier are covered with sheets of moraine matter, and upon the stagnant portion of this is a luxuriant growth of bushes, beneath which is a thickness of not less than 1000 feet

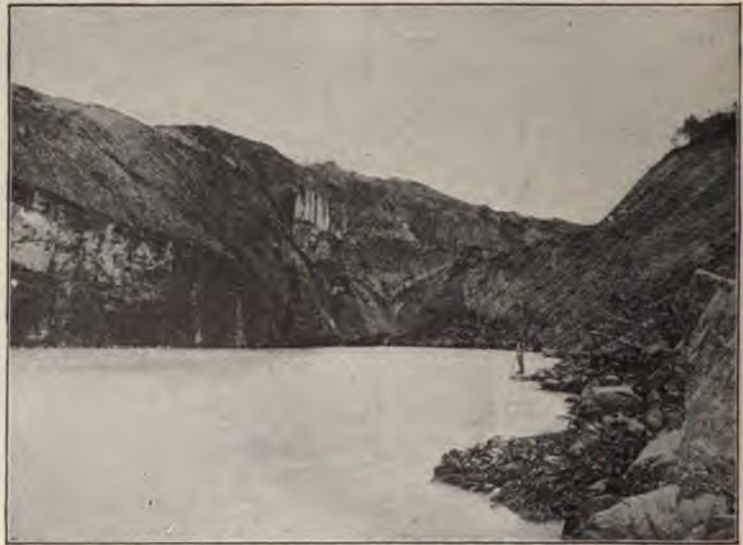


FIG. 60.— River issuing from the Malaspina Glacier, Alaska. (U. S. G. S.)

of ice. About the margin of the ice-sheet, small lakes are formed, the water being held in place by the ice barrier, but these lakes are subject to great fluctuations, and often their waters escape through tunnels in the ice. In some of these lakes stratified deposits are made by the inflowing streams. Innumerable streams, some of them quite large, rise from under the glacier, and many others flowing from the north pass under the free margin of the ice by means of long tunnels. All of these streams are loaded to their utmost capacity with sediment, gravel, and boulders; by blocking up their own openings from the ice, they likewise cause the deposition of sand, gravel, and boulders within their tunnels, which, when the glacier retreats, will be left standing as the gravel ridges called *åsars*, while conical mounds are built up where the streams burst from under the ice, and sometimes, owing to the great pressure, rise like fountains. This kind of deposition is characteristic of

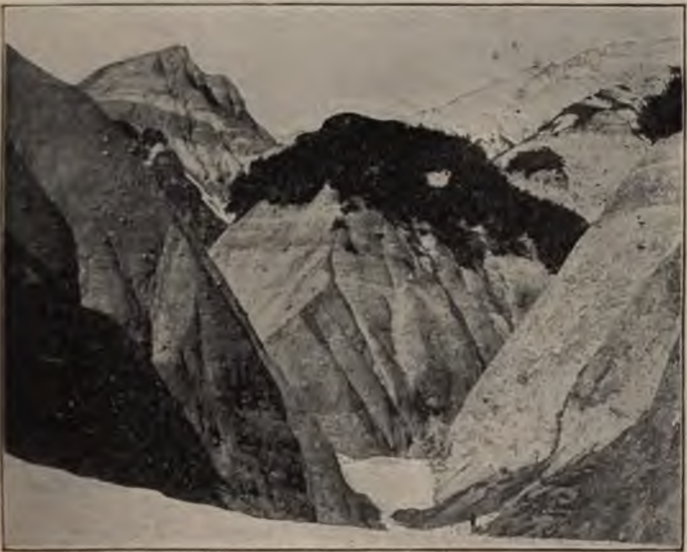


FIG. 61.—The Chaix Hills, Alaska. Moraine material stratified by water. (U. S. G. S.)

retreating ice-sheets, such as the Malaspina; in advancing glaciers denudation will prevail over deposition.

Iceberg Deposits. — When a glacier flows into the sea, it continues to advance until the buoyant power of the water is sufficient to raise and float it; as ice can endure very little strain, great masses are thus broken off and float away as icebergs. Icebergs are thus seen to be, as indeed they always are, derived from land ice and not from the freezing of sea-water. The iceberg will, of course, carry with it whatever parts of the glacial débris are contained within or upon that particular fragment of the glacier, and drops this load over the sea-bottom, as the berg gradually melts. As the Greenland icebergs sometimes drift as far south as the Azores, glacial boulders are scattered all over the bed of the North Atlantic, and thus we see how large blocks may be em-

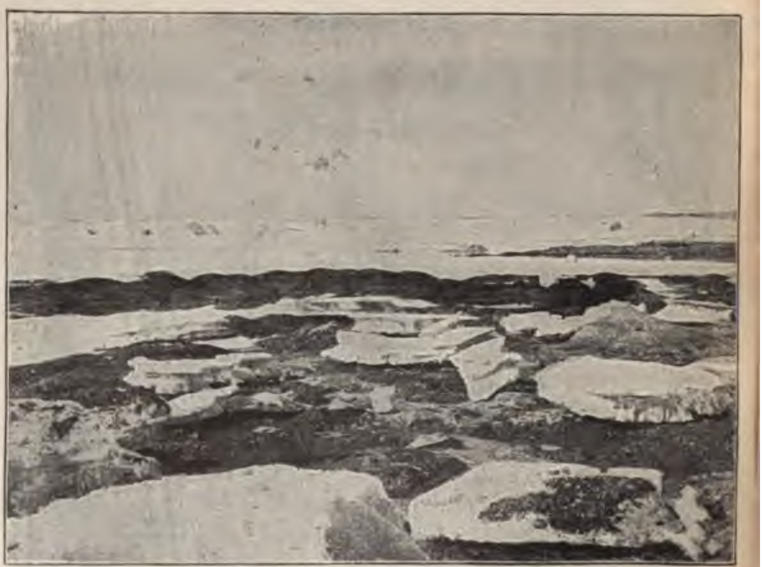


FIG. 62. — Deposit partly made by stranded ice, west coast of Greenland. (Photograph by Libbey.)

bedded in stratified deposits very far from the place where they were torn from their parent ledges.

Coast Ice Deposits. — In high latitudes with intensely cold winters, great fields of ice (the ice-foot) are formed by the freezing of sea-water along the shore. The ice-foot becomes loaded with great masses of rock, part of which is thrown down from overhanging cliffs by the action of frost, part picked up from the shore-line by the ice forming around it. In summer the coast ice breaks up and floats away with its load of blocks and boulders, distributing them over the sea-bottom just as icebergs do. In storms great masses of coast ice are often driven on the shore, where they may pile up to heights of fifty feet or more, carrying some of the boulders above the levels at which they were picked up. The coast of Labrador is covered for long distances with boulders thus transported, as are many other Arctic shores. Great masses of rock are thus transported in the Baltic, and the divers report that in the Copenhagen Sound the sunken wrecks of vessels are covered with ice-borne blocks.

CHAPTER IX

RECONSTRUCTIVE PROCESSES — MARINE AND ESTUARINE DEPOSITS

VI. Marine Deposits

The sea is the great theatre of sedimentary accumulation, and rocks of marine origin form by far the largest part of the present land surfaces. Important as other classes of deposits may be, all of them together are very much less so than those laid down in the ocean and the waters immediately connected with it. There is great variety in the sedimentary deposits made in the sea, which change in accordance with the depth of water, the nature of the coast rocks, the force of winds and tides, and the nearness or remoteness of the mouths of rivers. Large land-locked seas, like the Gulf of Mexico and the Mediterranean, again, have deposits more or less different from those of the open ocean, a difference which is largely due to the absence or insignificance of the tide, and the reduced force of the waves.

It is important to remember that the actual line of meeting of sea and land is not the structural margin of the continent, for the water may cover a broad submerged shelf of the latter. For 100 miles east from the coast of New Jersey the water deepens very gradually to the 100-fathom line, whence it shelves very steeply to the profound oceanic abyss. The 100-fathom line, which may be far out, or close inshore, generally represents the true margin of the continental platform. (See Fig. 63.)

Marine deposits may be classified primarily in accordance with the depth of water in which they were laid down, one of the most valuable guides to the history of ancient rocks, and secondarily in accordance with the nature of the material of which they are composed, and the processes by which they were accumulated. The classification proposed by Murray and Renard from a study of the great collections of modern marine deposits made by the "Challenger" expedition is as follows:—

MARINE DEPOSITS

1. Littoral Deposits, between high and low water marks.	Sands, gravels, muds, etc.	I. Terrigenous Deposits formed in deep and shallow water, close to land masses.
2. Shallow-water Deposits between low-water mark and 100 fathoms.	Sands, gravels, muds, etc.	
3. Deep-sea Deposits beyond 100 fathoms.	Coral Mud. Volcanic Mud. Green Mud and Sand. Blue Mud. Red Mud.	
	Foraminiferal Ooze. Pteropod Ooze. Diatom Ooze. Radiolarian Ooze. Red Clay.	II. Pelagic Deposits, formed in deep water removed from land.

The material brought into the sea by rivers, or washed from the shore by waves, is partly mechanically suspended and partly dissolved; the former will be deposited when the moving water is no longer able to transport it, while the latter is, to a large extent, extracted from solution by the agency of animals and plants, though some of it remains permanently dissolved. The sorting power of water, which is as conspicuous in the sea as in lakes or rivers, arranges the mechanically borne sediments according to the coarseness and fineness of their constituent particles, at the same time effecting a rough separation of the materials according to their mineralogical composition. Marine deposits are thus always stratified, though in cases when deposition is continued for long periods without interruption, thick masses, not obviously divided into layers, may be accumulated, but this is exceptional in those parts of the sea where deposition is most rapid.

1. **Littoral Deposits** are laid down between high and low tide marks and a little beyond the low-water mark, in very shallow water. These are made up of the coarsest materials, boulders, coarse gravel, and sand, though mud may accumulate in holes and sheltered situations, even within this zone. The principal grinding action of the surf is exerted between tide marks, and the undertow and tidal currents continually sweep out the finer particles to deeper and quieter water, leaving the coarser fragments behind. Mineralogically, these coarser fragments may be of any kind, depending upon the rocks of the coast and the material supplied by neighbouring rivers, but most frequently they are quartzose, which is due to the superior hardness of that mineral.

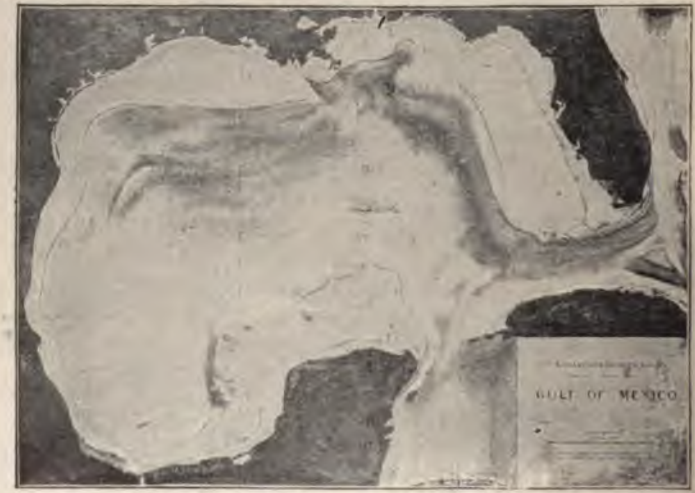


FIG. 63.—Basin of the Gulf of Mexico, showing the submerged margin of the continental platform and the steep descent of the bottom at the 100-fathom line. Vertical scale much exaggerated. (From a model by the U. S. Coast Survey.)

Littoral deposits are thickest toward the shore, thinning out to an edge seaward, where they dovetail in with finer materials, because the coarser fragments are carried farther out at some times than at others. Where, for long distances, no large rivers enter the sea, the materials are all derived from the wear of the coast, and the distribution of coarse and fine deposits is more regular and uniform, and gravel beds may extend as far as ten miles from the coast. The regularity of arrangement is interfered with by conflicting currents, and in eddies of quieter water will be found areas of finer deposits. Beds laid down in very shallow water are apt to be characterized by irregularities of stratification, known as false or current bedding; ripple marks and tracks of animals are other indications of the immediate proximity of the shore.

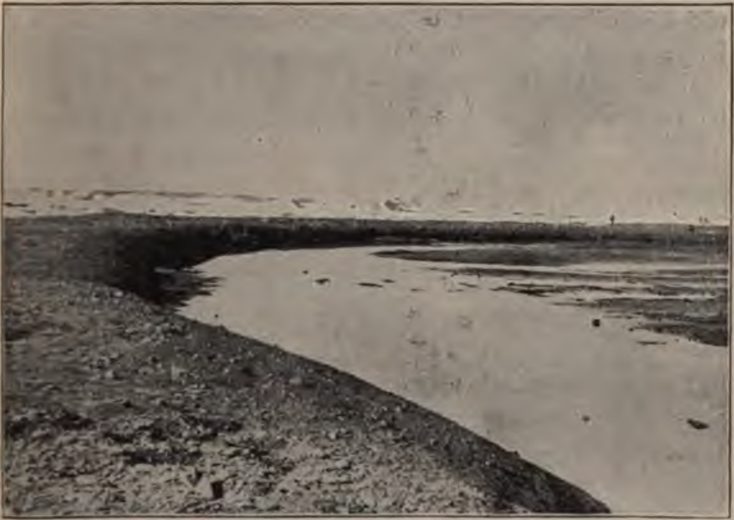


FIG. 64. — Littoral deposits on the west coast of Greenland. The angular pieces transported by ice. (Photograph by Libbey.)

It will at once be evident that no great thickness of shallow-water deposits can be formed, unless the sea-bottom is sinking, because, otherwise, the water would soon be filled up and deposition cease at that point. If the rate of subsidence be very slow, deposition may shoal the water and thus extend the seaward range of the coarse materials, forming broad belts of them, while, if the rates of deposition and sinking be nearly equal, the coarser deposits will be restricted to long and narrow bands, running parallel with the coasts. If, on the other hand, subsidence takes place at a rapid rate, the water will be deepened, the coast will retreat, and where coarse materials were before gathered, only the finer will now be accumulated. Thus in the same vertical line will be formed rocks which indicate very different depths of water.

2. **Shallow-water Deposits.** — Beyond the low-tide mark, and for a distance out to sea which depends upon the slope of the bottom, the sea-bed is ordinarily covered with sand. If, as along the eastern coast of the United States, the water deepens very gradually and the 100-fathom line is far from the shore, sand will be found 100 to 150 miles out, growing finer and finer with the increasing depth. Throughout this whole belt wave action is exerted on the bottom, though to a very insignificant extent in the deeper parts, but the stratification is regular and uniform, and the materials are widely and evenly distributed. The characteristic deposit of this zone is siliceous sand, though under exceptional circumstances, considerable areas of muds and clays may be formed. Thus, south of Block Island is a large triangular patch of clay which invades the sand area, and several large mud holes occur off the entrance to New York Bay. The action of the waves and shore currents transports the sand along the coast for long

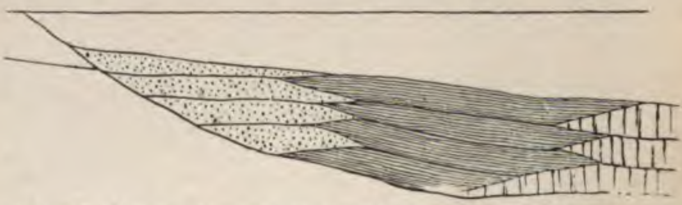


FIG. 65. — Diagram illustrating the change of materials on the sea-bottom and the dovetailed edges of sandy, clayey, and calcareous beds. Owing to the great exaggeration of the vertical scale, the beds appear unduly irregular.

distances from its place of origin. An instance of this is the Atlantic coast of Florida, which has a siliceous sand belt that cannot have been derived from the peninsula.

Organic deposits are much less common in shallow water than are the terrigenous, and yet under favourable conditions they are developed on a very extensive scale. The most important of such conditions are warm water and the presence of ocean currents which bring abundant supplies of food. The sea is constantly receiving from the land materials in solution, of which the most important are the carbonate and sulphate of lime. Many classes of marine animals extract the $CaCO_3$ from the sea-water and form it into hard parts, either as external shells and tests, or as internal skeletons. There is also good reason to believe that some, at least, of these organisms are able to convert the sulphate into the carbonate.

The classes of marine organisms which at present or in times past have played the most important part in the accumulation of calcareous material are: the Foraminifera, Corals, Echinoderms, and Molluscs; but other groups contribute extensively to the same result. The Foraminifera do not accumulate with sufficient rapidity to add largely to the calcareous deposits of shallow water, and will therefore be considered in connection with the deep-sea formations.

Corals.—The animals of this group are of many varieties of form, size, and habit, and by no means all of them are important as rock-makers. The solitary corals, for example, are widely distributed in the deep sea, but are never sufficiently abundant to form deposits by themselves. Those corals which do accumulate in great masses, and are known as reef-builders, form compound colonies or stocks, in which hundreds or thousands of individuals are united. The adult corals are stationary, but the newly hatched young are worm-like, free-swimming larvæ. When the young animal establishes itself in a suitable place, it develops into a *polyp*, or fleshy sac, with a mouth surrounded by rows of tentacles, and then by budding or partial division (fission) gives rise to great numbers of other polyps, which are connected together by a tissue common to them all. In this compound mass is secreted a skeleton of carbonate of lime, which reproduces the form of the colony and, in most cases, displays cells for the individual polyps. The great variety of form shown by these compound colonies is determined by the mode of budding or fission and the relative position of the newer to the older polyps. Thus, some are like trees, others like bushes; some form flat, irregular plates, while others grow into great dome-like masses.

The reef corals have, at present, a restricted distribution, and can flourish only where several favourable conditions are found united. They are preëminently shallow-water animals and can live only in depths of less than twenty fathoms. They also require a high temperature, and they cease wherever the average temperature of the water for the coldest month is below 68° F.; this is the minimum, and for full luxuriance a higher temperature is necessary. Another requisite is sea-water of full salinity and uncontaminated with mud; hence, corals cannot live at the mouth of a river, which, even if it brings down no sediment, freshens the water and is thus fatal to the polyps. Another condition favourable to the growth of corals is the presence of ocean currents, not too rapid, which bring abundant supplies of food, and they flourish best in the broken waters of heavy surf, which gives the necessary oxygen and prevents the smothering of the polyps in the calcareous silt and débris of the reef. In short, the reef corals are tropical, marine, shallow-water animals, and their reefs are widely spread throughout the warmer seas of the globe, but they do not always occur where we should naturally expect to find them.

A coral reef is not built, as many people imagine, by the industry of the polyps — these furnish the material, by extracting lime salts from the water and forming solid skeletons; the actual construction is largely the work of the waves, for the corals live within the limits of wave action. The coral colonies are scattered over the sea-bottom, much like vegetation on the land, scantily in some places, thickly in others, and in still others they are absent. The waves, especially in storms, break up the masses of coral, which are much weakened by the borings of many kinds of marine animals, and the surf grinds them down to fragments of all sizes, from large blocks to the finest and most impalpable mud. The process is the same as with the ordinary rocks of the coast, only the material differs, and thus are formed boulders, pebbles, sand and mud, all of coral fragments. The many animals which feed upon coral greatly facilitate this work, partly by boring into the masses, partly by grinding the smaller fragments into fine powder. Considerable masses of calcareous débris are added by the shells and tests of the various animals which live in and about the reef, and the coral-like seaweeds, called *Nullipores*, contribute an important quota. All of this material is ceaselessly ground up by the waves, distributed by tides and currents, and brought to rest in quiet waters. A single deposit of two or three inches in thickness has been observed to form between tides, after a gale along the

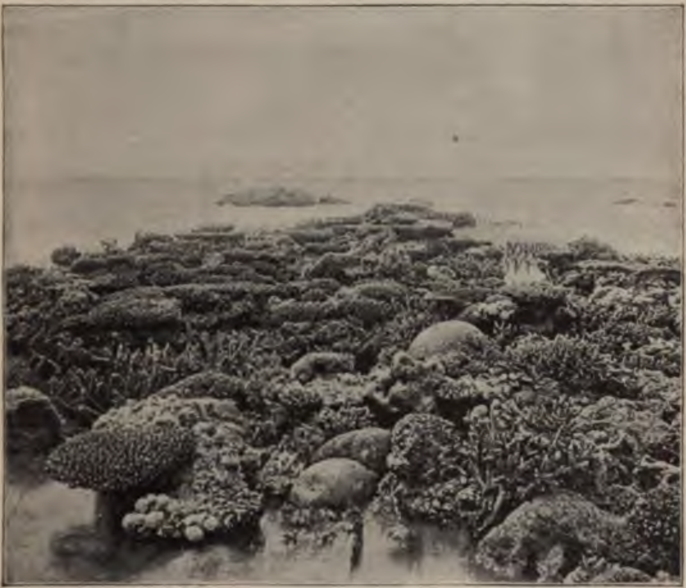


FIG. 66.—Patch of corals on the Great Barrier Reef of Australia. (Savile Kent.)

Florida reefs, and in storms the water is often discoloured and turbid for miles around the reef. The sea-water dissolves and redeposits $CaCO_3$, cementing the fragments into a firm rock, which, especially after exposure to the air, may become very hard.

By these processes several varieties of rock are formed, corresponding, in all but the material, to the ordinary marine deposits. In one form the standing and unbroken colonies are filled up with calcareous débris and enclosed in solid masses. Coral conglomerate or breccia is a cemented mass of coral pebbles or angular pieces, or is made up of fragments of an older coral rock. Reef rock is the dense and solid mass formed by the cementing of the finer débris which accumulates in quiet water. It is important to notice that even under the microscope reef rock frequently shows no trace of organic structure, and is a definite proof that the absence of such structure is not a sufficient reason for denying the organic origin of a rock. The interior of growing masses which are still alive on the outside, and have never been broken up, may be so crystallized by the action of the sea-water that the organic structure is obscured or destroyed. On the beach is formed a curious

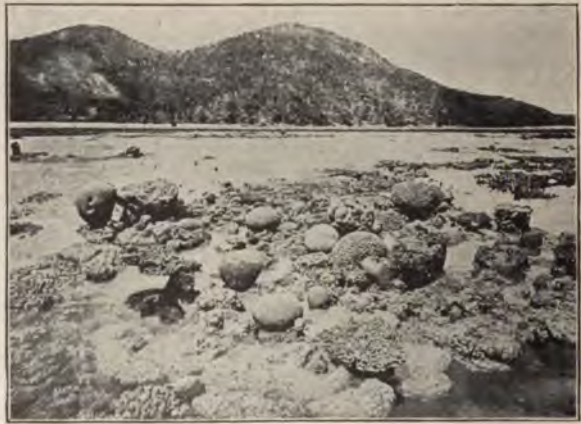


FIG. 67.—Corals on the Great Barrier Reef of Australia, mostly different from those in Fig. 66. (Savile Kent.)

rock called *oölite*, which is made up of minute spherules of $CaCO_3$ cemented into a mass not unlike fish-roe in appearance. This is due to the deposition of $CaCO_3$ from solution around tiny grains of calcareous sand, until the spherules are built up and cemented together.

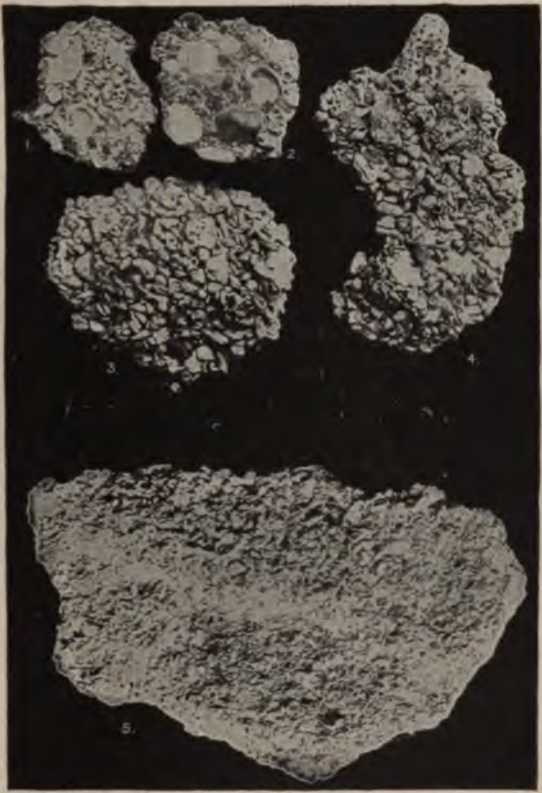


FIG. 68.—Various forms of modern coral limestone. (Savile Kent.)

The growth of coral ceases when the reef extends up to low-water mark, but the waves continue their work and throw up débris and build up a platform, upon which they establish a beach of calcareous sand. The latter may be further piled up by the winds into dunes and solidified by the cementing action of percolating rain-water. According to circumstances, the new platform may be an extension of the shore or an island like the Florida Keys.

Coral reefs are classed according to their relation to the shore, and are of three kinds. (1) Fringing reefs are those attached directly to the land, though the exposed part may be at some distance out from the shore and separated from it by a shallow channel with coral bottom. The width of a fringing reef is determined by the slope of the sea-bottom, being narrower on a steep grade, broader on a gentle one. (2) Barrier reefs are farther out from shore, to which the reef is parallel in a general way, and separated by a broad and often quite deep channel. The distinction between the two kinds of reefs is not very sharply drawn, for the same reef may be fringing in parts of its course and a barrier in others. Even at the present time barrier reefs are sometimes constructed on an enormous scale. A great barrier reef runs parallel to nearly the whole north shore of Cuba, while the barrier reef of Australia, the largest known, extends, with some breaks, for over 1200 miles along the northeast coast of Australia, from which it is distant 20 to 80 miles; its breadth varies from 10 to 90 miles, though but little of this width is exposed above water; its sea-face is in some places more than 1800 feet high (*i.e.* above the sea-bottom, not the surface). (3) Atolls are coral islands of irregularly circular shape, which usually enclose a central lagoon and frequently, as in the Pacific, rise from the profoundest depths. The way in which such islands have been built up is still a subject of much controversy, and limitations of space forbid its discussion here.

Dolomitization. — A process has been observed in the closed lagoons of certain atolls which is significant as throwing light upon a very difficult problem, that of the formation of dolomite or magnesian limestone (see p. 213). In the closed lagoon, shut off entirely from the sea, the isolated body of sea-water becomes considerably concentrated by evaporation. All sea-water contains chloride of magnesium ($MgCl$), and this percolating into the coral rock, by double decomposition with $CaCO_3$, forms $MgCO_3$. The transformation takes place much more readily when the $CaCO_3$ is in the form of aragonite, as is the case in many shells and corals.

Mollusca. — The ordinary shell-fish (Mollusca) supply a very large amount of calcareous material for the formation of shallow-water limestones, especially in the neighbourhood of the coasts. The shells accumulate in great banks, frequently, though not always, mingled with more or less sand and mud, and when gathered below the limit of violent wave action, they are entire, embedded in finer material, which is calcareous or not, according to the nature of the débris swept out from the shore. More commonly the shells are ground by the waves into fragments, making shell sand and mud, which is then cemented into a more or less compact mass. The coquina rock of Florida is an example of a recently made shell limestone (though it is forming no longer), and among the rocks of the earth's crust are many immense limestones which were accumulated in this way.

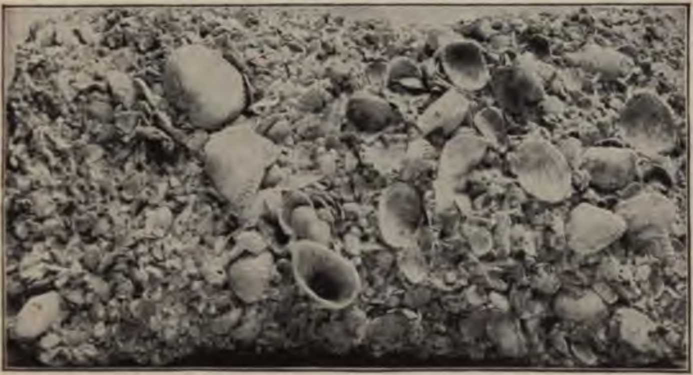


FIG. 69. — Modern shell limestone (Coquina) from Florida.

Echinodermata. — This group of marine animals, which includes the starfishes, sea-urchins, crinoids or sea-lilies, etc., is made up of forms which all secrete skeletons of calcareous plates, and which contribute largely to the formation of marine limestones. At the present day, however, they seldom build up any extensive masses unassisted, but in former ages of the world's history they did so on a great scale. This is particularly true of the crinoids (sea-lilies or feather-stars), which have now become comparatively rare, but many ancient limestones are composed almost entirely of their remains, and especially of their hard and heavy stems.

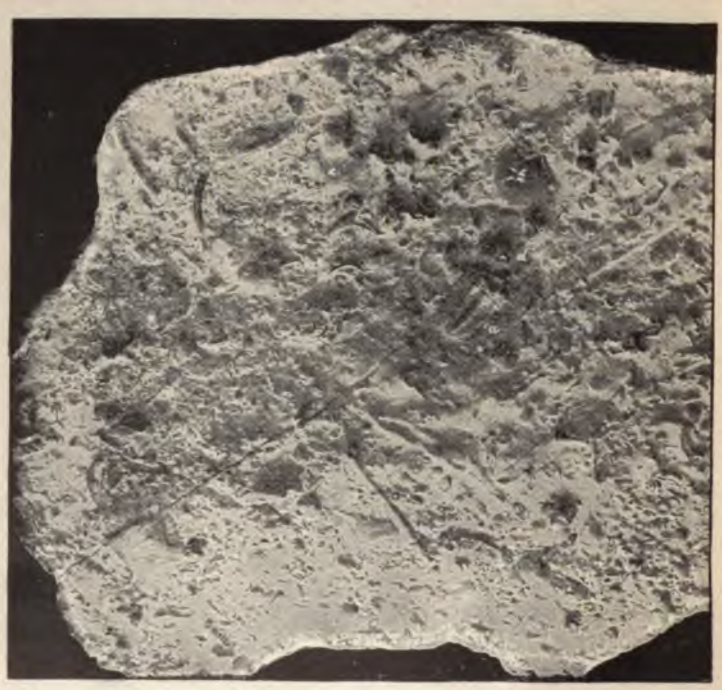


FIG. 70.—Ancient limestone composed of various kinds of organisms.

Limestone Banks. — In favourable situations immense submarine plateaus or banks are built up in shallow waters by the accumulated remains of all sorts of lime-secreting animals, corals, echinoderms, molluscs, worms, and Foraminifera. These are well exemplified in the Gulf of Mexico and the Caribbean Sea by the great banks along the west coast of Florida, the Yucatan bank, and the plateau which extends from the coast of Nicaragua almost to Jamaica. On these banks the luxuriance and fulness of life are astonishing, myriads of animals flourishing in the warm waters, and abundantly supplied with food by the great ocean currents which sweep over the banks. Innumerable molluscs, echinoderms, and calcareous worms are continually dying and adding their hard parts to the sea-floor; the waves and tides sweep calcareous sand and mud from the coral reefs over the flats, and all of these masses are rapidly consolidated into rock.

An example of a limestone bank in moderately deep water is the Pourtalès plateau, which extends southward from the Florida Keys, and is covered by 90 to 300 fathoms of water. "The bottom is rocky, rather rough, and consists of a recent limestone, continually, though slowly increasing from the accumulation of the calcareous débris of the numerous small corals, echinoderms, and molluscs, living on its surface. These débris are consolidated by tubes of serpulæ; the interstices are filled up by Foraminifera and further smoothed over by nullipores. — The region of this recent limestone ceases at a depth varying from 250 to 350 fathoms, and beyond it comes the trough of the straits." (A. Agassiz.)

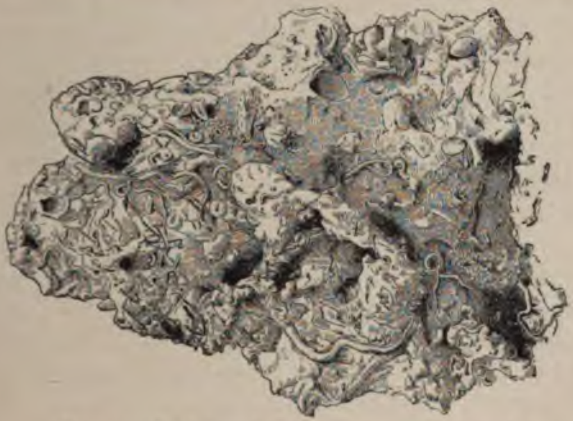


FIG. 71. — Rock from Pourtalès plateau. (A. Agassiz.)

It is not known how thick these modern limestone banks are, but some indication is given by the raised terrace of modern limestone which occurs in northern Yucatan. In this are caverns which descend through more than 400 feet of such rock (without reaching the bottom), all of which is formed from the hard parts of the same species of animals as still abound in the neighbouring seas.

Chemical Deposits. — It is not known just how important a part is played by chemical precipitation in the formation of marine deposits, but probably a greater one than has been generally supposed. Rivers which bring in quantities of $CaCO_3$ in solution may so overload the sea with this substance (for sea-water will dissolve little of it) that more or less is precipitated in the neighbourhood of the land. On the coast of Asia Minor, for example, are large areas of sandstone and conglomerate, formed within recent times by the precipitation of $CaCO_3$ in masses of sand and gravel, binding them into hard rock. Similar examples are known elsewhere. There is also some reason to believe that the decay of marine animals evolves sufficient carbonate of ammonia to convert the sulphate of lime into the carbonate by double decomposition, and to precipitate the latter in some quantity.

3. **Deep-sea Deposits.** — The 100-fathom line is by Murray and Renard regarded as the boundary between shallow and deep water, for it generally marks the edge of the continental shelf, from which the bottom rises very gently to the land, but slopes abruptly down to the oceanic depression. The great bulk of the material derived from the waste of the land is thrown down upon the continental shelf, within the 100-fathom line, but the finer particles are carried farther out and subside in deeper and quieter water. A considerable quantity of the finest sedimentary particles remains long suspended in sea-water, especially in the cold water of the polar seas. On the continental slopes, extending from the 100-fathom line to the bottom of the great oceanic abysses, are laid down most of the very fine materials derived from the land, which are grouped together under the somewhat indefinite term, *mud*.

a. **Terrigenous Deposits** are composed of materials chiefly derived from the shore, and occur in the less profound depths.

(1) *Blue Mud.*—The materials of this deposit, which are principally, though not altogether, derived from the land, are very heterogeneous. Quartz grains in an excessively fine state of subdivision are very abundant; clay is often a considerable ingredient, and then the mud is plastic when wet, but it is usually more earthy than clay-like. Minute particles of other terrigenous minerals, like felspar, hornblende, augite, etc., are common. $CaCO_3$ is almost always present, averaging 7%, and in some instances rising to 25%; this is due chiefly to the foraminiferal shells, both of those species which live at the surface and those which live on the bottom. Siliceous organisms are also present to the average amount of 3%, and are principally diatoms, radiolarians, and spicules of sponges. Glauconite is found in nearly all the samples. The blue colour of this mud is due to the sulphide of iron, and the organic matter which prevents the oxidation of the sulphide. Of the terrigenous deep-sea deposits blue mud is the most extensively developed; it is estimated as covering 14,500,000 square miles of the sea-bottom, and surrounds almost all coasts, and fills enclosed basins like the Mediterranean and even the Arctic Ocean. The depths at which blue mud is found range from 125 to 2800 fathoms.

(2) *Red Mud* is a local development, which occurs principally upon the Atlantic coast of Brazil, and in the Yellow Sea of China. Silt of this character, the red colour of which is due to Fe_2O_3, is brought down in large quantities by the Amazon and the Orinoco. Foraminiferal shells are abundant; radiolarians very rare.

(3) *Green Mud* is much the same in character as the blue mud, but owes its green colour to the higher percentage of glauconite which it contains.

(4) *Green Sand* is granular in appearance, and is made up largely of grains of glauconite and casts in that material of the interior of foraminiferal shells, together with nearly 50% of $CaCO_3$. The green sands occur in shallower water than the muds, and often within the 100-fathom line, as in the case of a deposit of this kind which is now forming off the coast of Georgia and the Carolinas. The estimated area of the green muds and sands is 1,000,000 square miles.

(5) *Volcanic Muds.* — In the deeper water surrounding volcanic islands are deposits of fine mud made from the disintegration of volcanic rocks, mixed with considerable clay, and also calcareous matter derived from organisms.

b. The **Pelagic Deposits** are those, the materials of which are not directly derived from the land, but consist of matters carried to the sea in solution and extracted from the sea-water by the agency of organisms, together with volcanic substances in a more or less advanced stage of decomposition. Only rarely are terrigenous materials found in these deposits, as, for example, off the west coast of Africa, where fine sand, carried by the wind from the Sahara, is found in deep water, and ice-borne fragments are common in high latitudes. The pelagic deposits are found far from land, and to a great extent, in the deepest oceanic abysses. In these profound depths the rate of accumulation is almost inconceivably slow, and the remains of extinct animals still lie exposed, or but slightly covered, upon the ocean floor.

(1) *Foraminiferal Ooze.* — The Foraminifera are minute animals, each one a tiny speck of jelly, most of which, in spite of their extreme simplicity of structure, have the power of secreting very beautiful and complex shells of $CaCO_3$. The species which are of importance in this connection are those which live in infinite multitudes at the surface of the ocean, and the most abundant at the present time are those which belong to the genus *Globigerina*, whence this deposit is frequently called Globigerina ooze. These surface Foraminifera flourish best in warm water and follow the warm currents, often into quite high latitudes. Their shells, which drop to the bottom as the occupants die, are present in almost all marine deposits, but near land the terrigenous materials preponderate to such a degree that the Foraminifera make up but a slight proportion of the deposit. In deeper water, where the wash from the land does not come, the foraminiferal shells grow relatively much more abundant, and when 30% or more of a given sample of the bottom consists of them, it is classed as a foraminiferal ooze. Other organisms which secrete calcareous shells or tests always contribute more or less to these oozes (coral mud, echinoderms,

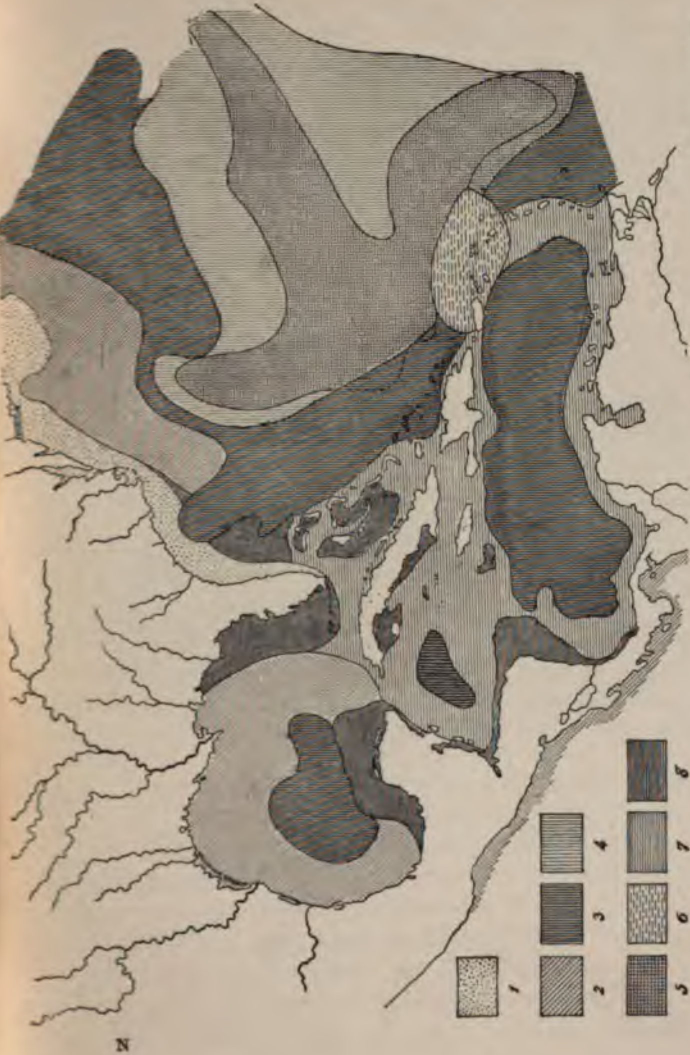


FIG. 72.—Map of marine deposits in the western Atlantic. 1. Sand. 2. Muds and clays. 3. Foraminiferal ooze, modified. 4. Foraminiferal ooze, oceanic. 5. Red clay. 6. Pteropod ooze. 7. Pteropod ooze, modified. 8. Limestone banks. (Map modified from Murray and Renard.)

molluscs, nullipores, etc.). The deposit is purest and most typical in the medium depths of the ocean, far from any land; in such places the ooze may contain as much as 90% $CaCO_3$ and is white, while nearer land the slight admixture of terrigenous minerals gives a pink, grey, brown, or other colour to the mass. Below the depth of 2500 fathoms the proportion of $CaCO_3$ becomes much diminished, owing to the increasing percentage of CO_2 in the sea-water, which attacks and dissolves these delicate shells.

The foraminiferal oozes have a vast geographical extent, estimated at 49,520,000 square miles, and are especially developed in the Atlantic, though they are largely present in all except the polar seas, and range in depth from 400 to 2900 fathoms.

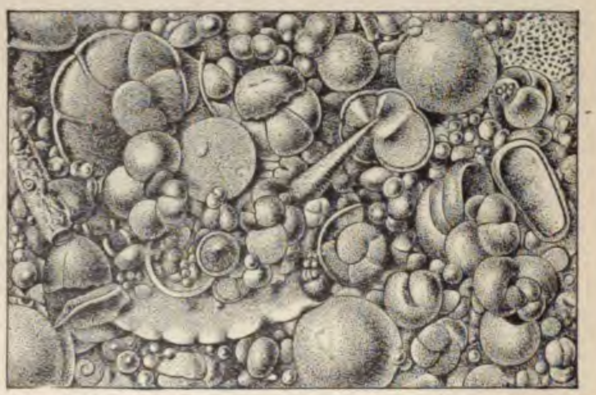


FIG. 73. — Foraminiferal ooze. × 20. (Agassiz after Murray and Renard.)

(2) *Pteropod Ooze.* — The thin and delicate shells of the molluscan groups, known as the pteropods and heteropods, abound at the surface of the warmer parts of the ocean, but their dead shells are found only in depths of less than 2000 fathoms. In shallow water (and even in greater depths near land) the shells are concealed by other kinds of material, but in moderate depths, far from any land, these shells sometimes become so frequent in the foraminiferal ooze as to give it a special character. In its typical development this pteropod ooze has been found only in the Atlan-

tic, where it covers some relatively small areas, in depths of 400 to 1500 fathoms.

(3) *Radiolarian Ooze.* — The organisms which we have so far considered secrete only shells or tests of $CaCO_3$, but this is not the only substance which is very extensively extracted from sea-water by living beings. Silica is also dissolved in sea-water, and various organisms construct their tests of that substance. The *Radiolaria* are, like the Foraminifera, a group of microscopic, unicellular animals, which secrete siliceous tests of the most exquisite delicacy and beauty; they live both at the surface and at the bottom of the sea. Radiolarian tests may be detected in all sorts of marine deposits of both deep and shallow water, but it is only in very profound depths that they occur in quantity sufficient to give character to the deposit. When 20% or more of a bottom deposit consists of radiolarian tests, it is called a radiolarian ooze, but clay and volcanic minerals make up most of the materials. This ooze has been found only in the Pacific and Indian oceans, where, it is estimated, it covers 2,290,000 square miles of the bottom, at depths of 2350 to 4475 fathoms.

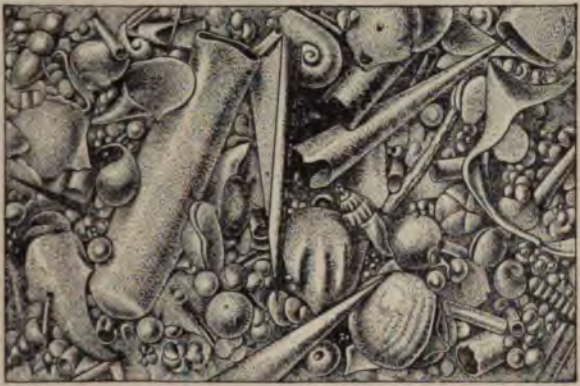


FIG. 74. — Pteropod ooze. × 4. (Agassiz after Murray and Renard.)

(4) *Diatom Ooze.* — In our study of fresh-water deposits we learned that the siliceous cases of the microscopic plants known as

diatoms form considerable accumulations in lakes and ponds, and they also flourish abundantly in brackish water and in the sea. Diatoms are found in many marine deposits, but in relatively small quantities. In the Antarctic Ocean, however, is an immense belt of ooze, believed to cover 10,880,000 square miles and extending around the globe, which is largely made up of their frustules. Besides the great Antarctic zone, an area of some 40,000 square miles is known in the North Pacific. The diatom ooze entirely resembles the fresh-water deposit, but may be distinguished by the presence of foraminiferal and radiolarian shells and tests. The depths at which this ooze is found are from 600 to 2000 fathoms.

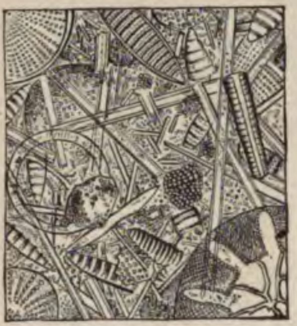


FIG. 75. — Diatom ooze. × 150. (Agassiz after Murray and Renard.)

(5) *Red Clay.* — The profoundest abysses of the ocean, far from any land, are covered with a deposit of red clay, which, though varying much in composition and colour, is yet of a quite uniform character. In these vast depths the foraminiferal shells are almost all dissolved by the carbonated sea-water, but some $CaCO_3$ is very generally present, averaging about 6%, and diminishing in quantity as the depth increases. In the less profound abysses the red clay passes gradually into the foraminiferal oozes, the number of shells increasing until the ooze-like character is attained. The clay is derived from the disintegration and decay of volcanic substances, especially pumice, which floats upon water, often for months, and drifts long distances in the ocean currents. The greater part of these volcanic materials is believed to be derived from terrestrial volcanoes, but the submarine vents doubtless contribute largely; particles of undecomposed volcanic minerals and glasses are also common. In some regions the clay is coloured chocolate brown by the oxide of manganese, and many separate nodules of this substance are

found. The excessive slowness with which this abysmal deposit is formed, is shown by the occurrence, in recognizable quantities, of meteoric iron, which reaches the earth in the form of meteorites, or "shooting stars," and by the presence of the remains of animals which have long been extinct.

Of all the oceanic deposits the red clay is much the most widely extended, covering 51,500,000 square miles of the bottom. Almost four-fifths of this vast area are in the great depths of the Pacific; the shallower Atlantic has much more of the foraminiferal ooze than of the red clay. The observed range in depth is from 2225 to 3950 fathoms.

Comparing the marine deposits now accumulating in the sea with the rocks of evidently marine origin which form most of the land, we find that the great bulk of these rocks, the sandstones, slates, and limestones, are such as are formed in water of shallow and moderate depths, while only rarely do we discover a rock, like chalk, that implies really deep water.

VII. Estuarine Deposits

An estuary is a wide opening at the mouth of a river into which the sea has penetrated by the depression of the land. In such bodies of water the tide often scours with much force. Estuaries abound along our Atlantic coast, Delaware and Chesapeake bays and the mouth of the Hudson being excellent examples of such. The water in them is brackish, and unfavourable to abundant aquatic life, for only a limited number of marine animals, and fewer fresh-water ones, flourish in brackish water.

Estuarine deposits are, in general, much like those of the sea, except that they are apt to be of a finer grain for a given depth of water; muds are abundantly laid down, especially in the more sheltered nooks and bays, with fine and coarse sands and gravels in the more exposed situations. The sands are apt to show a confused stratification from the conflicting currents and eddies in which they are deposited, but with horizontal layers formed at slack water. Extensive mud flats often surround an estuary, especially if the rise and fall of the tide be great. On these flats, exposed during low tide to the sun and air, sun-cracks are formed on the drying surface, and these, together with the prints of raindrops and the tracks of land animals, will be preserved when the incoming tide, advancing too gently to scour the slightly hardened surface of the flat, deposits a fresh layer of sediment upon it. If the estuary be the opening of a large river, considerable deposits of river sediment will, in times of flood, be laid down upon the other beds, producing an alternation of fresh and brackish water beds. On the coast of North Carolina somewhat peculiar conditions obtain; the low sand-spits thrown up by the waves enclose extensive shallow sounds, into which the tide enters by only narrow openings, but which have numerous streams flowing into them. At high water the incoming tide acts as a barrier, damming back the river waters, checking their velocity, and causing them to deposit their burdens of sediment. In course of time, the sounds must be silted up by the rivers.

For reasons that we have already discussed, estuaries are not favourable to either fresh-water or marine organisms, and hence estuarine deposits do not contain any great variety of remains of either group. These remains may, however, represent numerous individuals, sufficient sometimes to form limestone layers. Diatoms may also accumulate in great quantities, as in one of the Baltic harbours, where they form 18,000 cubic feet of deposit annually. On the other hand, estuaries are often favourably situated for the reception and preservation of the remains of land animals and plants which are swept into them by streams.

The Consolidation of Sediments

The processes of deposition upon the land and beneath the water, which we have so far been studying, result, for the most part, only in the bringing together of great masses of loose and incoherent material. If such masses are to be properly compared with the hard rocks of the earth's crust, it will be necessary to show that loose sediments may be consolidated and rendered hard and firm, like the latter. This is not difficult, for we have abundant evidence to prove that such consolidation actually does take place, and in a variety of ways.

(1) *Consolidation by Weight of Sediment.*—When deposited on a sinking sea-bottom, sediments often accumulate in masses of great thickness, and in such cases the lower portions must tend to consolidate from the weight of the overlying masses. Of course, such a process cannot be directly observed in modern accumulations, because only the surface of them is accessible, but from the analogy of observed facts we may safely infer that this weight is not without effect.

(2) *Consolidation by Cement.*—Sediment is often penetrated by percolating waters, which carry in solution various cementing substances, such as SiO_2, $CaCO_3$, $FeCO_3$, etc., and the deposition of these materials in the interstices of the loose sediment will bind the particles into a firm rock. This process we have already had occasion to observe in several instances, as in the coral reefs, the drift-sand rock of Bermuda, the modern sandstones on the coast of Asia Minor, and many others. In all of these cases the cementing substance is $CaCO_3$, but other modern rocks are known in which Fe_2O_3, formed by the oxidation of $FeCO_3$, plays the same rôle. Both of these substances are very common as cements among the ancient rocks. A cementing effect may also be produced by reactions within the mass of the sediment itself, as is seen in the solidification of many volcanic ashes mingled with water to form tuffs.

(3) *Consolidation through Heat.*—This may be local, as in the neighbourhood of volcanoes, or general and due to the internal heat of the earth. For sediment to reach great thickness it must subside, and this subsidence brings the lower parts of the mass deep down into the crust, where they are invaded by the earth's interior heat, and baked as bricks are burnt in a kiln. This process is likewise one which cannot be directly observed, but the effects of molten lava upon loose sediments may be watched, and the consolidating power of heat has been tested experimentally.

(4) *Consolidation by Lateral Pressure.*—This is probably the most widely acting and important agency of consolidation. Though it acts so gradually and at such depths that we cannot see it in operation, yet the inference is, none the less, a safe one. We shall see later that very many of the stratified rocks are no longer in the nearly horizontal position in which they were first laid down, but have been folded and fractured through the operation of great lateral pressures. The more intensely folded and compressed any rock has been, the harder has it become, not only through the mechanical pressure, but by the heat and the chemical changes which such compression generates. In addition to this, we know from experiment that loose materials may be consolidated by powerful compression. Certain exceptional rocks of very ancient date are known, which are almost as incoherent as when first accumulated, but these all retain their original horizontal position and have not been compressed. It must not be supposed, however, that only compressed sediments have become hard, for great areas of scarcely disturbed rocks are found, which are perfectly solid and firm; here some other solidifying agent has been at work.

There are certain other features in which the loose modern sediments differ from the older and harder rocks, such as joints, and cleavage which divides many rocks into thin plates, independently of the planes of stratification. These may be shown, however, to be structures which the rocks have acquired after their formation, and therefore need not be discussed here.

The parallel is now complete between the sediments which we may observe to-day in the process of accumulation, and the hard stratified rocks which make up by far the largest part of the dry land. For all these ancient rocks we may find a counterpart in sediments now forming, and we may conclude with perfect confidence that the ancient rocks were formed by the same agencies as the modern accumulations. Every rock contains a more or less legible record of its own history.

Summary. — The brief survey of dynamical geology which we have now taken has brought to light many facts of the highest significance for the interpretation of the earth's history as recorded in the rocks. The materials of the earth's crust we have found to be in a state of ceaseless, though very slow, circulation, disintegrating here, accumulating there. Volcanoes bring up from the interior of the earth molten and fragmental materials, which consolidate into glassy or crystalline rocks, or beds of cinders and tuffs. Earthquakes shatter the rocks and shake down masses from the cliffs, while changes of level bring the sea over the land, or raise parts of the sea-bottom into land surfaces.

Everywhere over the land and along the seacoast processes of disintegration are at work upon the rocks, decomposing them chemically and breaking them up mechanically. Rain, wind, frost, changes of temperature, underground waters, rivers, glaciers, the currents and waves of the sea, all take part in this work, each in its own characteristic way. The products of this destruction are transported by various agents, especially the rivers, to lakes and the sea, though some find a resting-place, for a longer or shorter time, upon the land. Part of this material is dissolved in water, but the greater part is mechanically suspended. The suspended portion is sorted by the power of water and laid down in sheets and layers upon the beds of lakes or the ocean, forming stratified masses, while dissolved materials are largely extracted by the agency of animals and plants, and deposited under water as accumulations of calcareous or siliceous sediments. By various processes, these incoherent and loose masses are consolidated; they may be upheaved to form new land surfaces, and a new cycle of destruction and reconstruction will begin. These changes we have studied in order to obtain a key for the interpretation of the earth's history, which is recorded in the rocks, and we have found that these records may be so interpreted by the aid of processes which are still at work. We have yet much to learn, however, before such a systematic history can be attempted, and first to study the ways in which the rocks are actually arranged and the disturbances which they have undergone: this is *structural geology*, the next division of our subject.

PART II

STRUCTURAL GEOLOGY

CHAPTER X

THE ROCKS OF THE EARTH'S CRUST—IGNEOUS ROCKS

In the first section of this book we made a study of the processes and agencies which are still at work upon and within the earth, tending to modify it in one or other particular. We there found that slow but ceaseless cycles of change take place on the earth's surface and that a continual circulation of material is going on.

We have now to take up the second branch of our subject, that of *structural geology*, which deals with the materials of the earth's crust, their mode of occurrence, and their arrangement into great masses. Structural geology is, however, not merely a descriptive study; hand in hand with the examination of the rock-masses must go the attempt to explain their structure, and to show how they have come to be as we find them. Dynamical principles must be continually called in to interpret the facts of structure, and many of the principles of the construction, destruction, and reconstruction of rocks find their application in the study of structure.

This application cannot, in all cases, be made with confidence and certainty, both because a given structure may often be referred, with equal probability, to different processes, and because certain of the great dynamical agencies are so slow and gradual in their mode of operation, that no one has ever been able to observe them at work. In this latter class of cases the agency must be inferred, not from anything which we have actually seen accomplished, but from the traces which it has left in the structure. Under such circumstances, it need not surprise us to find that the explanation is not always easy and obvious, but may be very problematical, and that great differences of opinion may arise concerning the rightful interpretation of a complex region.

Here, as in all other provinces of geology, the historical standpoint is the dominant one. Our object is to learn, not only the agencies which have produced the structures and the way in which they operated, but also the successive steps by which the structures originated, the order in which they occurred, and their geological date. Thus they may be coördinated into the great history of the earth, which it is the main problem of geology to construct.

ROCKS

The distinction between a rock and a mineral is not always an easy one for the beginner to grasp, yet it is essential that he should do so. A *Rock* is any extensive constituent of the earth's crust, which may consist, though rarely, of a single mineral, but in the great majority of cases is a mechanical mixture of two or more minerals. A rock thus has seldom a definite chemical composition, or crystalline form, or homogeneous internal structure. An examination with the microscope almost always shows that a rock is an aggregate of distinct minerals, which may be all of one kind, or of many different kinds, in varying proportions. Rocks, then, are mechanical mixtures, and their properties vary in proportion to their various ingredients, while minerals are chemical compounds (see p. 9).

In ordinary speech the term *rock* is held to imply a certain degree of solidity and hardness, but in geological usage the word is not so restricted. Incoherent masses of sand and clay are regarded as being rocks, quite as much as the hardest granites.

The classification of rocks is a very difficult and obscure problem, and would be so, even were our knowledge much more complete and exhaustive than it is. There are, therefore, great diversities in the various schemes of classification which have been proposed and which are still in use, and all such schemes require great modifications to meet continually advancing knowledge.

Bearing in mind the principle, already emphasized so often, that geology is primarily a historical study, the most logical scheme of classification is obviously one that, so far as possible, is *genetic*, that is to say, one which expresses in brief the history and mode of formation of the rocks. Other criteria, such as texture and chemical and mineralogical composition, must be employed for the minor subdivisions. On this genetic principle we may divide all rocks into three primary classes or groups.

A. *Igneous Rocks*, those which were melted and have solidified by cooling. Texture glassy or crystalline.

B. *Sedimentary Rocks*, those which have been laid down (almost always) under water, by mechanical, chemical, and organic processes. Rocks composed of more or less rounded and worn fragments, seldom crystalline.

C. *Metamorphic Rocks*, those which have been profoundly changed from their original sedimentary or igneous character, often with the formation of new mineral compounds in them. Texture fragmental or crystalline.

IGNEOUS ROCKS

We have every reason to believe that the igneous rocks were the first to be formed, and arose, in the first instance, from the cooling of the surface of the molten globe. In later ages and at the present time, the igneous rocks have a much more deep-seated origin and have either forced their way to the surface, or have cooled and solidified at varying depths beneath it. The igneous rocks being thus the primitive ones, all the others have been derived, either directly or indirectly, from them. The products of the chemical disintegration or mechanical abrasion of the igneous rocks have furnished the materials out of which the sedimentary rocks were formed, at least in the first instance.

The igneous rocks are massive, as distinguished from stratified, and though sometimes presenting a deceptive appearance of stratification, may always, with a little care, be readily distinguished from the truly stratified rocks. The term *massive* is, indeed, frequently used for these rocks, in the same sense as igneous, and *eruptive rocks* is another term, meaning the same thing, though eruptive is also employed in a more restricted sense.

Characteristic differences appear between those igneous masses which have solidified deep within the earth and have been brought to light only by the denudation and removal of the overlying rock-masses, and those which have cooled at or near the surface of the ground. The former are called *plutonic* (or intrusive) and the latter *volcanic* (or extrusive). Between the two may be found every form of transition, and the terms *volcanic* and *plutonic* are now employed for description rather than for classification.

The *texture* of an igneous rock means the size, shape, and mode of aggregation of its constituent minerals. Texture is a very important means of determining the circumstances under which the rock was formed, and hence great attention is paid to it. Since texture responds so accurately to the circumstances of solidification, rate of cooling, pressure, etc., all the varieties shade into one another by imperceptible gradations and form a continuous series. Nevertheless, it is necessary to distinguish and name the more important kinds.

Among the igneous rocks are found four principal types of texture, with several minor varieties.

1. *Glassy.* — Here the rock is a glass or slag, without distinct minerals in it, though the incipient stages of crystallization, in the form of globules and hair-like rods, are often observable with the microscope. When the glass or slag is made frothy by the bubbles of escaping steam and gas, the texture is said to be *vesicular*, *scoriaceous*, or *pumiceous*, according to the abundance of the bubbles. These are varieties of the glassy texture, though other kinds may also be vesicular. A vesicular rock in which the steam-holes have been filled up by the subsequent deposition of some

mineral, is called *amygdaloidal*, a term derived from the Greek word for almond.

2. The *Compact* (or Felsitic) texture is characterized by the formation of exceedingly minute crystals, too small to be seen by the unassisted eye, giving the rock a homogeneous, but stony and not glassy appearance. If the crystals are too minute to be identified even by the aid of the microscope, it is said to be *cryptocrystalline*, and when such identification can be made, it is called *microcrystalline.*

3. *Porphyritic.* — In rocks of this texture are large, isolated crystals, called *phenocrysts*, embedded in a ground mass, which may be glassy or made up of minute crystals. The phenocrysts may have sharp edges and well-formed faces, or they may have irregular and corroded surfaces. The porphyritic texture indicates two distinct phases of crystallization. The first is the formation of the phenocrysts, which remain suspended in the molten mass, or *magma*, and are often corroded and partially redissolved by it. These crystals are said to be of *intratelluric* origin, because formed before the eruption of the lava, and such crystals are showered out of certain active volcanoes at the present time. Stromboli (see p. 36), for example, ejects quantities of large and perfect augite crystals. There is reason to believe, however, that not all phenocrysts are thus intratelluric, but that the first phase of crystallization sometimes takes place after the ejection of the molten mass. The second phase consists in the formation of the ground mass, which may be glassy, minutely crystalline, or both.

4. *Granitoid.* — In this texture the rock is wholly crystalline, without ground mass or interstitial paste. The component grains, which may be fine or very coarse, are of quite uniform size, and as the crystals have interfered with one another in the process of formation, they have rarely acquired their proper crystalline shape. Such grains are said to be *allotriomorphic.*

An additional texture which should be mentioned is the *fragmental.* This is represented by the accumulations of the fragmental products ejected by volcanoes (see p. 51), agglomerates, bombs, lapilli, ashes, etc. Many such materials accumulate in bodies of water and are there sorted and stratified and, it may be, mingled with more or less sand and mud and other truly sedimentary material. Rocks formed in this manner partake of the nature of both the igneous and sedimentary classes, and may be referred to either group, or regarded as a series intermediate between the other two and in a measure connecting them. These rocks will here be treated as a special subdivision, under the name of pyroclastic rocks.

In our studies of the products of modern volcanoes, we saw that the same molten mass will give rise to rocks of very different appearance in its different parts, according to the circumstances of rapidity of cooling, pressure, etc. We may now express this in somewhat more general form and say that the texture of an igneous rock is determined by the several factors which affect the molten mass during consolidation. Of such factors may be mentioned the chemical composition, temperature, rate of cooling, degree of pressure, and the quantity present of dissolved vapours and gases, which are called *mineralizers*. In one and the same continuous mass of rock we also find great differences of mineralogical composition, a process of segregation taking place in the molten magma. When this occurs, it is the general rule that the mass becomes more basic toward the periphery.

Chemical composition determines the fusibility of a rock at a given temperature. The least fusible rocks are, on the one hand, those which contain large quantities of silica, 60 to 75% (acid rocks), and, on the other, those which contain less than 40% of silica (ultrabasic rocks). The most fusible rocks are those with an intermediate percentage of silica (basic rocks), and among these the fusibility increases, as the percentage of silica diminishes, until the lower limit is reached. The effect of chemical composition upon texture is seen in the rapidity with which the less fusible rocks chill and stiffen, and therefore the greater frequency with which they form glasses.

Chemical composition is, however, important in this connection chiefly through its effect upon the rate of solidification. We have already learned (p. 12) that solidification very generally takes place by a process of crystallization, and this requires time. Hence, very rapid cooling results in a glass, but the microscope reveals the incipient stages of crystallization in many of even the glassy rocks. A somewhat slower rate of solidification produces a cryptocrystalline rock, and successively slower rates bring about the porphyritic, microcrystalline, and granitoid textures. Large crystals form slowly, and other things being equal, the larger the component crystals of a rock, the more slowly has it consolidated.

Pressure is of importance in preventing the rapid escape of the vapours and gases contained in the molten mass, and hence frothy, scoriaceous, and vesicular textures cannot be produced under high pressures. Pressure is also believed to be necessary for the formation of many phenocrysts in porphyritic rocks.

The mineralizers, such as steam, hydrochloric acid, and other vapours, determine the crystallization of many minerals, which refuse to crystallize in the absence of such vapours. Variations in the quantity of mineralizers present in different parts of the same mass, occasion corresponding differences in the local textures. The well-known Obsidian Cliff, in the Yellowstone National Park, is formed by a great sheet of igneous rock, made up of alternating layers of glassy and microcrystalline rock, a difference which is referred to varying proportions of mineralizers present in different parts of the molten mass.

It must not be supposed that a molten magma consists merely of a number of fused minerals, mechanically mixed together and having no effect upon one another. If such were the case, the minerals in cooling should all crystallize in the order of their fusibility, the least fusible forming first, and the most fusible last. This is not what we find, and many facts which cannot be discussed here have led petrographers to the belief that a molten magma is a *solution* of certain compounds in others, and that crystallization occurs in the order of solubility, as the point of saturation for particular compounds is successively reached by the cooling mass.

Similar phenomena may be observed among the metals. If strips of copper be thrown into a vessel of melted tin, the latter will dissolve the copper at a temperature far below that at which the copper would melt alone.

In a rock magma the crystallization of the more and more soluble minerals will proceed regularly, provided the pressure and rate of cooling continue constant. As these conditions are, however, subject to variation, it frequently happens that the more soluble minerals begin to crystallize before the less soluble have all been formed, and thus the periods of formation of two or more kinds of minerals partly overlap.

Usually, the mode of formation of the different kinds of minerals in a solidifying mass is as follows. First to form are apatite, the metallic oxides (magnetite, ilmenite) and sulphides (pyrites), zircon, and titanite. " Next come the ferro-magnesian silicates, olivine, biotite, the pyroxenes, and hornblende. Next follow the felspars and felspathoids, nepheline and leucite, but their period often laps well back into that of the ferro-magnesian group. Last of all, if excess of silica remains, it yields quartz. In the variations of pressure and temperature, it may and often does happen that crystals are again redissolved, or resorbed, as it is called, and it may also happen that after one series of minerals, usually of large size and intratelluric origin, have formed, the series is again repeated on a small scale, as far back as the ferro-magnesian silicates. Minerals of a so-called second generation thus result, but they are always much smaller than the phenocrysts and are characteristic of the ground mass.

" It results from what has been said that the residual magma is increasingly siliceous up to the final consolidation, for the earliest crystallizations are largely pure oxides. It is also a striking fact that the least fusible minerals, the felspars and quartz, are the last to crystallize." (Kemp.)

A very considerable number of minerals are found in the igneous rocks, but comparatively few in any large quantity. It thus becomes necessary to distinguish between the *essential* minerals of a rock and the *accessory* ones. The essential minerals are those the presence of which is necessary to the formation of a given kind of rock, while the accessory minerals are those which occur in small quantities and which may be present or absent, without affecting the character of the rock. The distinction is necessary and useful, but is sometimes arbitrary.

Another necessary distinction is that between *original* and *secondary* minerals. Original minerals were formed with or before the rock of which they are constituents, and secondary minerals are produced by the alteration or reconstruction of the original ones.

With comparatively few exceptions, the igneous rocks are made up of some felspar or felspathoid, together with one or more of the pyroxenes, amphiboles, micas, or quartz. Magnetite is also very common.

What was said above with regard to the difficulty of classifying rocks, applies more especially to the igneous group, because of the way in which the various kinds shade into one another, since even the same molten mass may differentiate into several species, showing not only differences of texture, but marked changes of chemical and mineralogical composition. In an elementary work, like the present, only a meagre outline of the subject can be attempted, for the microscopic study of rocks, or petrography, has now become an independent science of great scope and interest, and cannot be compressed into a few pages.

The classification of the igneous rocks now most generally adopted, is made upon a threefold method, according to texture, and chemical and mineralogical composition. In the following table (modified from Kemp's) the textures are given in vertical order, while transversely the arrangement is mineralogical, chiefly in accordance with the principal felspar. In this manner the acidic rocks come at the left side of the table and the basic at the right side. The percentages of silica are given on a lower line of the table.

Acidic ← IGNEOUS ROCKS → Basic

Glassy	Acid Glasses Obsidian, Perlite, Pumice, Pitchstone.				Andesite Obsidian.				Basic Glasses Scoriæ, Tachylyte, Basalt Obsidian.	
	Chief Felspar Orthoclase			Chief Felspar Plagioclase				Nepheline, Leucite	No Felspar	
	Biotite and or Hornblende and or Augite			Biotite and or Hornblende		Pyroxenes			Augite and or Hornblende and or Biotite	
	+ Quartz.	Quartz.	Leucite, Nepheline.	+ Quartz.	− Quartz.	− Olivine.	+ Olivine.		− Olivine.	+ Olivine.
Porphyritic	Rhyolite (Quartz Porphyry).	Trachyte.	Phonolite (rare). Leucite Phonolite (very rare).	Dacite.	Andesite.	Augite Andesite. Olivine free Basalt. Diabase.	Basalt Dolerite. Olivine Diabase.	Nepheline and Leucite Basalts. A series of basaltic rocks which are hardly to be dis-	Augitite. Extremely rare in America.	Limburgite.
Compact	Quartz Felsite.	Felsite.				Basalt.	Olivine Basalt.	tinguished from the ordinary basalts except with the microscope. Very rare in America.		
Granitoid	Granite.	Syenite.	Nepheline Syenite (rare). Leucite Syenite (very rare).	Quartz. Diorite.	Diorite.	(Diabase) Gabbro. Anorthosite Norite.	(Olivine Diabase) Olivine Gabbro. Olivine Norite.	Theralite (extremely rare).	Pyroxenite. Hornblendite.	Peridotite.
SiO_2	80-65 %	65-55 %	60-50 %	70-60 %	65-50 %	55-45 %		45-38 %	55-40 %	45-30 %
Granite Family		Syenite Family		Diorite Family		Basalt Family			Ultrabasic Rocks	

The acidic rocks are so called because they are rich in silica (which is an acid), but they have only small quantities of lime, magnesia, and iron; hence they are very infusible, of low specific gravity, and generally of light colours. The basic rocks, thus named because of the predominance of the bases, have much smaller percentages of silica and higher ones of lime, magnesia, and iron; the latter substances act as fluxes, making the basic rocks much more fusible, as well as giving them a higher specific gravity and darker colour. The distinction between acidic and basic rocks cannot be very sharply drawn, because the two kinds are connected by every variety of intermediate gradation. The same is true, however, of all the divisions given in the table, which is apt to produce a false impression of sharply distinguished groups of rocks, such as do not occur in nature.

As a general rule, the glassy and porphyritic textures characterize those rocks which have solidified at the surface of the ground, or not very far below it, while the granitoid types have cooled slowly and at great depths; but there are exceptions to both statements. Between the glassy and porphyritic textures at one end of the series and the granitoid at the other, comes the felsitic, which represents an intermediate rate of cooling and intermediate depths within the earth as the place of solidification.

The division of the igneous rocks into families is made primarily in accordance with the mineralogical composition, with subdivisions according to texture. This method gives us five principal groups.

I. The Granite Family

The molten magma, which on solidification gives rise to the rocks of this group, is very rich in silica (65 to 75%) and has from 10 to 15% of alumina; the quantity of alkalies (Na and K) is relatively large (6 to 8%), and there are small amounts of iron oxides (2 to 4%), magnesia (1 to 2%), and lime (1 to 4%). In the process of consolidation the principal minerals formed are orthoclase and quartz, with smaller amounts of oligoclase, iron oxide, and of the ferro-magnesian minerals, biotite or hornblende.

Differences of texture, produced in the manner already described, give rise to rocks of totally different appearance, which it is difficult to imagine are of similar or identical composition.

Obsidian is a volcanic glass, which is usually black or dark brown or green (but sometimes blue, red, or yellow). It breaks with a shell-like fracture, and in very thin pieces is translucent. The microscope shows that its dark colour and opacity are due to the quantity of minute "crystallites," the incipient stages of crystals, which are present in great numbers. The name *obsidian* is used for the various kinds of volcanic glass in which the percentage of water is small, and so for exact description a prefix is necessary, such as *rhyolite obsidian*, *andesite obsidian*. Though the glasses are of varying composition, by far the greater number of them belong to the granite family. When the glass is divided by concentric cracks, due to shrinkage on cooling, so as to form onion-like spherules, it is called *Perlite*.

Pitchstone has much the same appearance as obsidian, but contains from 5 to 10% of water.

Pumice is a glass blown up by the bubbles of escaping steam and other vapours into a rock froth, so light that it will float upon water. A very similar substance is produced when a jet of steam is blown through the melted slag from an iron furnace.

It not infrequently happens that, in course of time, the volcanic rocks become *devitrified*, losing their glassy texture and assuming a stony one. The homogeneous rock becomes converted into a mass of extremely minute crystals of quartz and felspar, and the original glassy texture is then shown only by the lines of flow, or by the perlitic character, which are not affected by the change.

Rhyolite ordinarily occurs as the lava outflow of a granitic magma, cooled rapidly, but yet more slowly than obsidian. The texture is porphyritic, the phenocrysts being chiefly quartz, and the glassy form of orthoclase known as sanidine, while the ferromagnesian minerals are present in very much smaller quantities, and of these the commonest is biotite. The phenocrysts are embedded in a ground mass of minute felspar crystals and a varying proportion of glass. Other names used for rhyolite are *liparite* and *quartz trachyte*. The rhyolites are exceedingly common in the western part of the United States. The *Felsites* are very dense, fine-grained, and light-coloured rocks, in which phenocrysts are absent or scanty; they are ancient rocks which have been formed in different ways, by the devitrification of obsidians and rhyolites, by the recrystallization of tuffs, and by original cooling from fusion.

Quartz Porphyry shades imperceptibly into rhyolite or felsite on the one hand, and into granite on the other; it is made up of phenocrysts of quartz, or of quartz and orthoclase, in a finely crystalline ground mass of the same minerals. If the phenocrysts are all of orthoclase, the rock is called a *felspar porphyry*. The difference from rhyolite consists in the greater compactness and density of the rock and the absence of glassy ground mass.

Granite. — The granites are thoroughly crystalline rocks, of typically granitoid texture, to which they have given the name, and without any ground mass. The grains have not their proper crystalline shape, the separate minerals interfering with each other in the process of crystallization. The characteristic minerals are quartz, orthoclase, some acid plagioclase, muscovite, and biotite; magnetite and apatite are always present, though in small quantities. The variations in granite are principally in the ferromagnesian minerals. Thus we have *muscovite granite*, with white mica only; *granitite*, with biotite only; *hornblende granite*, the hornblende replacing the mica, or in addition to biotite; *augite granite*, with augite and biotite. Those in which the percentage of soda is high are called *soda-granites*. When the dark silicates and mica are all absent, the rock is called a *binary granite*.

The colour of granite is dark or light in accordance with the proportion of dark silicates present, while the shades of the felspar determine whether the rock shall be red, pink, or white. The texture of granite varies from fine to very coarse, and in some cases there is found a ground mass of ordinary granite, in which are embedded very large crystals of orthoclase; this is sometimes called a *granite porphyry*.

II. The Syenite Family

In this family the magma much resembles that of the granite group, except that the quantity of silica is less (55 to 65 %); hence it is nearly or quite taken up in the formation of silicates, leaving little or none to crystallize out separately as quartz, and orthoclase is thus the chief mineral. The two families are connected by many transitional rocks.

Syenite obsidian is indistinguishable, except by chemical analysis, from the glasses of the preceding family, but it is much less common.

Trachyte is a volcanic rock, consisting of phenocrysts of sanidine in a ground mass of minute felspar crystals, but having little or no glass, together with more or less biotite, amphibole, or pyroxene, according to which we get the varieties *mica*, *amphibole*, or *pyroxene trachyte.* In America the trachytes are very much less abundant than the rhyolites.

Phonolite differs from trachyte in the higher percentage of soda which it contains, and in the presence of the felspathoid nepheline or leucite, or both. The name is derived from the ringing sound which thin plates of the rock give out when struck with a hammer. Phonolites are quite rare rocks, and in this country the best-known locality for them is the Black Hills region of South Dakota.

Syenite is a thoroughly crystalline rock, without ground mass, and much resembling granite in appearance, but having no quartz. It is composed typically of orthoclase and hornblende, with plagioclase, apatite, and magnetite as accessories. When the hornblende is replaced by biotite, the rock is called *mica syenite*, and when by augite, *augite syenite.* The name *syenite* is sometimes given to the rock we have called "hornblende granite" (p. 198).

Nepheline Syenite is marked by the presence of nepheline, and bears the same relation to phonolite as syenite does to trachyte, being the granitoid crystallization of the same magma.

The syenites occur just as do the granites, but are not nearly so frequent.

III. The Diorite Family

The magma of these rocks has about the same silica percentages (55 to 65 %) as have the syenites, but the quantity of alkalies is less, while that of the lime and magnesia is greater. Hence orthoclase is absent or much less important, and the principal mineral is a soda-lime felspar. The textures display the usual variety from glassy to granitoid.

The glasses of this family (andesite obsidian) can be distinguished from those of the preceding groups only by chemical analysis, but they are rare.

Andesites are dark-coloured lavas of porphyritic or compact texture, composed of a glassy plagioclase felspar and some ferro-magnesian mineral, embedded in a ground mass of felspar needles and glass. In accordance with the nature of the predominant ferro-magnesian mineral, we have *hornblende andesite*, *biotite andesite*, and several varieties of *pyroxene andesite*. These rocks are very common in the western United States and along the Pacific coast of both North and South America; they are named from the Andes.

The **Dacites** differ from the andesites in having quartz, and therefore a higher percentage of silica.

The **Diorites** are the plutonic equivalents of the andesites and dacites, having granitoid texture, but they are usually of much finer grain than the granites and syenites. The ferro-magnesian mineral is usually green hornblende, but augite and other pyroxenes and biotite occur in the different varieties. Most diorites have a little quartz; but when this mineral becomes abundant, it gives a *quartz diorite*, which is related to the dacites as the typical diorite is to the andesites. A common name for the diorites is *greenstone*.

IV. The Basalt Family

In the magmas of this series the percentage of silica is much less than in the preceding groups (40 to 55 %), and the quantity of alkalies is small, while that of iron, magnesia, and lime is much greater. They are heavy, dark-coloured rocks, which generally weather red, from the oxidation of the FeO which they contain. The principal minerals are a plagioclase felspar, rich in lime (labradorite or anorthite), some kind of pyroxene, magnetite, and frequently olivine. There is a wide range of mineralogical composition and many varieties of rock occur in this family, but often these can be distinguished from one another only by the aid of the microscope.

Tachylyte is a basaltic glass, which is not at all common.

Basalt is a name of wide application covering many varieties, which, however, can seldom be distinguished by the unassisted eye. They are very common volcanic rocks, and most of the active volcanoes of the present day extrude basaltic lavas. In texture the basalts are ordinarily porphyritic, but they may be without phenocrysts, and consist of a finely crystalline mass. The ground mass is made up of tiny crystals, mingled with a dark glass.

The basalts are closely related to the andesites and connected with them by a number of transitional forms, but in the andesites the phenocrysts are principally felspars, which is not the case in the basalts. Those basalts which contain olivine in notable quantities are called *olivine basalt;* while those in which the felspar is replaced by leucite or nepheline are called *leucite* and *nepheline basalt,* respectively. Several other named varieties occur, but, for the most part, they require the aid of the microscope for their identification. A rare variety, found in New Mexico, California, and elsewhere, contains phenocrysts of quartz.

Trap is a useful field name for various sorts of dark, granular rocks, which cannot readily be distinguished by inspection. The term is often applied to diorite and especially to diabase.

Dolerite is a coarsely crystalline basaltic rock, which is either porphyritic or granitoid in texture.

Diabase is a rock of peculiar texture; the felspar crystals are long, narrow, and lath-shaped, and contain the dark minerals in their interstices. The trap rocks of the Palisades of the Hudson, and many localities in the Connecticut valley, New Jersey, Maryland, Virginia, and North Carolina, are diabase.

Gabbro is a term which is now used comprehensively to include the coarse-grained, plutonic phases of the various basaltic rocks, which are typically composed of plagioclase and pyroxene. *Olivine gabbro* and *hornblende gabbro* are names that explain themselves. *Norite,* or *hypersthene gabbro,* contains orthorhombic pyroxene. *Anorthosite* is nearly pure labradorite in large crystals, with little or no pyroxene: great masses of it occur in Canada and the Adirondack Mountains of New York.

NOTE. — Since the foregoing paragraphs were written, Professor Pirsson has described a group of basaltic rocks which have large, transparent phenocrysts of analcite with pyroxene, olivine, and other dark silicates embedded. These rocks are called *Monchiquites.*

V. THE ULTRABASIC ROCKS

These rocks have no felspars, and in most of them the quantity of silica is below 45 %, while that of magnesia is from 35 to 48 %; they are composed almost entirely of ferro-magnesian minerals.

Limburgite is made up of crystals of augite, olivine, and magnetite, embedded in a glassy ground mass.

Augitite is a similar rock, but without olivine.

Pyroxenite is a holocrystalline, plutonic rock composed of one or more varieties of pyroxene.

Hornblendite is a similar rock made up of hornblende.

The **Peridotites** are likewise plutonic rocks which are principally composed of olivine, with iron ore and some of the pyroxenes or hornblende.

The **Serpentine Rocks** are products of decomposition, and many of them have been formed from the peridotites, though some are derived from augitic rocks, such as gabbro, and others from hornblendic rocks. In rarer instances they have arisen from the alteration of acid rocks.

APPENDIX

THE PYROCLASTIC ROCKS

These rocks are formed out of the fragmental materials ejected from volcanoes. The materials are of course igneous, but the rocks themselves differ from the typical igneous rocks in several important respects. They have not been formed in their present state of aggregation by cooling from a molten mass, and in many cases they are more or less distinctly stratified. It seems best, therefore, to group them separately, under the name *pyroclastic*.

Volcanic Agglomerate or **Breccia** is a mass of angular blocks of lava, with which may be mingled fragments of sedimentary rocks, which the volcano has torn off from the sides of its chimney. The blocks may be loose or cemented together into hard rock by a filling of finer materials. Ordinarily the breccia is formed only near the vent, but sometimes it is developed on a great scale, as in the eastern part of the Yellowstone Park.

Tuffs are masses of volcanic ashes and dust, which accumulate in beds, either on the land or in bodies of water. Even in falling through the air, the particles are sorted, in some degree, in accordance with their size, and the tuffs are thus usually stratified, and sometimes have fossils in them. When accumulated under water, the ashes are, of course, stratified and may be mingled with more or less sedimentary débris. Such subaqueous tuffs pass into the ordinary sedimentary rocks, by the gradual diminution of the volcanic material. When examined under the microscope, even the finest tuffs are found to consist of crystals and particles of glass.

The volcanic breccias and tuffs may best be classified in accordance with the nature of the component fragments. Thus, we find rhyolite tuffs and breccias, andesite tuffs and breccias, basaltic tuffs and breccias, and the like.

CHAPTER XI

THE SEDIMENTARY ROCKS

THE materials of which the sedimentary rocks are composed were, in the first instance at least, derived from the chemical decay or mechanical abrasion of the igneous rocks, and hence they are often called derivative or secondary. They have been laid down under water (or, in a few instances, on land) and are therefore always stratified and, for the most part, are composed of rounded fragments, seldom crystalline.

Almost all the materials which we have found in the igneous rocks also occur, in a more or less worn and comminuted condition, in the sedimentary class. However, with the exception of quartz, the great bulk of the sedimentary materials consists of simpler and more stable compounds than the igneous minerals, from the decomposition of which they have been derived. The principal minerals which compose the sedimentary rocks are quartz (SiO_2), clay (Al_2O_3, 2 SiO_2, 2 H_2O), and the carbonate and sulphate of lime ($CaCO_3$, $CaSO_4$).

Quartz is a very simple and stable chemical compound, and hence, in the ordinary process of rock decay, it remains unchanged further than being broken up into smaller pieces and rounded by the action of wind or running water. Clay is derived principally from the decay of the felspars, and the lime compounds from the complex silicates containing lime, which are so frequent in the igneous rocks. These rocks also yield the iron oxides which are so widely diffused in the sedimentary class, though comparatively seldom in any very great quantity. Very many varieties of rocks are produced by the mixture of the siliceous (quartz), argillaceous (clay), and calcareous (lime) materials in varying proportions. The sorting out of material by water, according to its chemical nature, is usually imperfect, and changes from point to point, so that the sedimentary rocks have an even less definite chemical composition than have the igneous.

The most useful classification of the sedimentary rocks is, primarily, according to the mode of their formation, and secondarily, according to their composition. This gives two principal divisions: I, *the Aqueous Rocks*, or those laid down under water; II, *the Æolian Rocks*, those which were accumulated on land, which are of very limited extent and importance.

The aqueous rocks may be further divided into three classes: 1, Mechanical Deposits; 2, Chemical Precipitates; 3, Organic Accumulations.

I. AQUEOUS ROCKS

The rocks laid down under water form by far the largest and most important of the sedimentary series.

1. MECHANICAL DEPOSITS

These have resulted from the accumulation of débris derived from the destruction of preëxisting rocks, carried in mechanical suspension by moving water, whether waves, currents, or streams, and dropped when the velocity of the moving water was no longer sufficient to carry them. The study of the dynamical processes has already taught us that such accumulations are forming to-day in all kinds of bodies of water, and an examination of the rocks will show that similar accumulations have been made since the beginning of recorded geological time. Mineralogically, the mechanical deposits are of two principal kinds, the *siliceous* and the *argillaceous*. The sorting power of water has been sufficient to separate them roughly, though we find mixtures of the two in all proportions.

a. Siliceous Rocks

In these rocks the principal component is quartz in fragments of greater or less size, either angular, or more or less rounded by wear. Of the common rock-forming minerals quartz is the hardest and the one which best resists chemical change. Small quantities of other minerals, such as magnetite, mica, felspar, garnet, etc., are generally present.

Sand is made up of fine grains of quartz, not compacted together, but forming a loose, incoherent mass. River sands and those formed by the atmospheric disintegration of rocks commonly have angular grains, due to the splitting up of the quartz fragments along preëxisting flaws. Beach sands are more apt to be rounded, due to the constant wash of the surf.

Sandstone is a rock of varying degrees of hardness, the grains of sand being held together by a cement. The most important cementing substances are carbonate of lime, the oxides of iron, and silica. The sandstones with calcareous cement usually yield quickly to the action of the weather, because of the solubility of the cement. Those with ferruginous cement are much more durable and more highly coloured, being of various shades of red, yellow, and brown. Most durable of all are the siliceous cements.

Novaculite (or oilstone) is an exceedingly dense and fine-grained sandstone, the particles of which are as fine as those of clay. Its smoothness and hardness fit it admirably for sharpening fine tools. Extensive deposits of this rock occur in Arkansas.

Varieties of sandstone are produced by the conspicuous admixture of other minerals; thus, *micaceous sandstone* has abundant flakes and spangles of mica deposited along the planes of stratification. *Argillaceous sandstone* is composed of a more finely grained sand than the more typical sandstones, contains considerable quantities of clay, and is, in general, more thinly bedded. The flagstones, so largely used for pavement, are examples of such a rock, and split readily into slabs of almost any desired size.

Arkose or **Felspathic Sandstone** is a rock composed largely of cemented grains and fragments of felspar, which have been mechanically broken up by the action of water, but not chemically disintegrated. More or less sand is often mingled with the felspar grains.

Breccia is a rock made of large *angular* fragments cemented together. The fragments may be of any kind of material.

Gravel is composed of rounded, water-worn pebbles, varying in size from a pin-head up to cobblestones and boulders. The coarser kinds are often called *shingle*. Gravel may be composed of almost any kind of rock material, but the commonest pebbles are of quartz, because of its greater resistance to wear. Masses of quartz will be only rounded into pebbles, when other substances are ground into fine silt, or chemically disintegrated, and so washed into deeper water.

Conglomerate is a firm rock, made up of pebbles, embedded in a matrix of finer material, very generally sand. As above remarked with regard to gravel, the component pebbles of a conglomerate may be derived from any kind of hard rock, but siliceous pebbles are of most frequent occurrence. Different names are given to conglomerate, according to the character of the pebbles, as *quartz conglomerate*, *flint conglomerate*, *limestone conglomerate*, *granite conglomerate*, etc.

b. Argillaceous Rocks

These rocks contain a greater or less proportion of clay, but nearly always with large admixtures of other substances, such as exceedingly fine sand, felspathic mud, and the like. The particles of these rocks are extremely fine and are carried for long distances before settling to the bottom. Hence the muds and clays are distributed over wider areas than the gravels and sands, and deposits of them indicate quieter and, usually, but not always, deeper waters than the conglomerates and sandstones.

Kaolin, also called China or porcelain clay, is a nearly pure white clay, which is formed principally from the decay of the alkaline felspars of granitic rocks.

Potter's Clay is a somewhat less pure variety, having a considerable quantity (18 to 37%) of finely divided quartz, and small quantities of lime and iron.

Brick Clay is a still more impure mixture of sand and clay, with lime, magnesia, iron, potash, and soda. Clays with considerable percentages of iron burn red in the kiln, from the oxidation of their iron compounds into Fe_2O_3. Ordinary red bricks do not withstand high temperatures and cannot be used for the lining of furnaces, because the iron, alkalies, and alkaline earths which they contain cause the bricks to disintegrate.

Fire-clay is a nearly pure mixture of sand and clay, with only traces of iron, magnesia, or lime, and therefore burns to white or buff-coloured bricks, which will resist very high temperatures. Fire-clays occur frequently beneath coal seams, representing the ancient soil in which the coal plants grew. Such ancient fire-clays are often hard rocks, and must be ground up before using.

Mudstone is a rock which is composed of solidified clay or felspathic mud, or a mixture of the two, and which crumbles rapidly into mud when exposed to the action of the weather.

Shale is a finely stratified or laminated clay rock, formed from the solidification of mud and silt. In some of the paper shales there are as many as thirty or forty laminæ to the inch, each representing a separate process of deposition. Shales ordinarily contain more or less sand, and as this increases in quantity, they shade gradually into arenaceous shales and argillaceous sandstones, or by the increase of calcareous matter into limestones. *Bituminous shale* is coloured very dark or black by the carbonaceous matter with which it is saturated. When distilled, the bituminous shales yield hydrocarbons, and are of considerable economic importance; the carbonaceous matter may be of either animal or vegetable origin. Shales of this class grade into coals.

Marl is clay containing carbonate of lime, which rapidly crumbles on exposure to the weather.

2. CHEMICAL PRECIPITATES

Rocks which have been principally or entirely formed by chemical processes are, for the most part, of locally restricted extent, and are not at all comparable to the great masses of mechanical and organic sediments. This arises from the fact that the chemical processes occur in a conspicuous way only around the mouths of certain classes of springs (p. 128), and in closed bodies of water without outlet and subject to evaporation (p. 149).

The chemical precipitates may be classed under the following heads: *a*, Precipitates of the alkalies and alkaline earths; *b*, siliceous precipitates; *c*, ferruginous precipitates.

a. Precipitates of the Alkalies and Alkaline Earths

Calcareous Tufa or **Sinter, Travertine, Stalactite, Onyx Marbles,** are all forms of carbonate of lime deposited from solution, either around the vents of springs, or by percolating waters in limestone caverns or in lakes. These deposits are made of crystallized calcite (or aragonite), are very pure, and usually white, and more or less translucent, though they may be stained by other substances dissolved with the lime. In structure they are banded and show rings of growth, which distinguishes them from the organic limestones. The so-called "Mexican onyx" or "onyx marble" is a beautifully banded travertine derived from ancient spring deposits.

Oölite is a limestone composed of minute spherules of carbonate of lime, cemented into a more or less compact mass, somewhat resembling fish-roe, whence is derived the name, meaning "egg rock." The spherules are made up of concentric layers of carbonate of lime, deposited from solution around some nucleus, it may be a particle of sand or dust, or a calcareous fragment. The beach rock of a coral reef (p. 169) is made in this fashion, and calcareous sinter often has a similar structure. When the spheres are larger, resembling peas in size and shape, the rock is called *pisolite*.

Gypsum ($CaSO_4$, H_2O) is a rock as well as a mineral (see p. 23), and is deposited from solution in salt lakes and lagoons, in which evaporation balances the influx of water (p. 151). When pure, gypsum is white, but it is often coloured grey, brown, or red, by iron stains, and it may even be black. It forms compact, crystalline, or fibrous beds, looking like limestone, but much softer and not effervescing with acid; portions of the beds may consist of transparent selenite crystals. Gypsum sometimes occurs in the form of anhydrite ($CaSO_4$), but it is not known under what conditions the anhydrous sulphate has been deposited from solution.

Rock Salt ($NaCl$) is precipitated by evaporation from the dense brine of salt lakes and lagoons, following the deposition of gypsum, which explains the very common association of the two rocks in successive beds. The salt may be present only as an ingredient of shale (saline shale), or may form thin layers, indicating brief periods of deposition, followed by freshening of the water. Again, it may occur in enormously thick masses, the result of long-continued precipitation. One such mass, near Berlin, exceeds 5000 feet in thickness. Rock salt is often very pure, and then it is transparent and colourless; but it is frequently stained by iron, or mingled with dust blown into the lake or lagoon which deposited the salt, or mixed with clay and other mechanical sediments.

b. Siliceous Precipitates

These are much less common and extensive than the calcareous, and are formed under exceptional conditions.

Geyserite, or **Siliceous Sinter**, is deposited in dense and hard masses around the mouths of geysers, partly by the evaporation of the water which holds the silica in solution, and partly by the action of Algæ (see p. 130). Large terraces of this rock have been built up by the geysers of the Yellowstone Park. Geyserite also occurs as an uncompacted white powder.

Cherts (Flint or Hornstone) are exceedingly dense and fine-grained masses, which the microscope shows to be made up of very minute grains of chalcedony mixed with more or less amorphous silica and crystals of quartz. The mode of origin of these masses is not at all well understood, but is believed to be by precipitation from sea-water. In the Lake Superior region occur cherty rocks which are mixtures of chalcedony and carbonate of iron, from which the iron ores are derived by a process of weathering.

c. Ferruginous Precipitates

These rocks may, with almost equal propriety, be classed with those of organic origin, because, as we have already learned (p. 135), the concentration into beds of the iron, which is so widely diffused through nearly all rocks and soils, is chiefly due to the action of decomposing vegetable matter. But as the action is by means of the chemical effects of dead plants, and not by the activities of living ones, it will be best to retain the iron precipitates with the chemically formed rocks. Important as they are from an economic point of view, iron-ore beds are not extensive constituents of the earth's crust, and should be regarded as minerals rather than as rocks.

Ironstone is a general name for the various ores. Hæmatite occurs in strata and filling the cavities in limestone rocks. Limonite also occurs in strata, and at the present day is precipitated from solution in lakes. Siderite is found in beds, or mixed with chert or in clay concretions. Magnetite is associated with crystalline rocks, in which it often forms great masses and beds.

3. ORGANIC ACCUMULATIONS

The organically formed rocks are those whose materials were accumulated by living beings, on the death of which more or less of their substance was preserved, added to by successive generations, and finally compacted into rock. In preceding chapters we have read of these processes as going on at the present time, in peat bogs, in the coral reefs, shell banks, limestone plateaus, and organic oozes of the ocean. Similar processes have been at work in all ages of the earth's history since the first appearance of living things, and very extensive rocks have thus been built into the solid crust of the globe. An exact classification would require us to place certain of those rocks among the mechanical sediments, because the actual work of accumulation was performed by mechanical agencies, such as waves and currents. But it will be more convenient to examine together all those rocks which are principally made up of organic materials, especially as it is not always easy to distinguish the results of one mode of formation from those of the other.

a. Calcareous Accumulations

Limestone is a very abundant, important, and widely distributed rock, the commonest of the organic accumulations. It is composed of carbonate of lime in varying degrees of purity, hardness, fineness of grain, and crystalline texture. Sand or clay is frequently present as an impurity, and by an increase in these materials, the limestones pass gradually into sandstones and shales. In some varieties of limestone the organic nature of the rock is most obvious, shells, corals, crinoid stems, and the like being conspicuously shown, especially on weathered surfaces. In other kinds the microscope is required to make this organic nature clear; while in others, again, the calcareous materials have been so ground up by the action of the waves, that all traces of organic structure have disappeared. The example of the reef rock now forming in many coral reefs (p. 168) is a warning that the absence of even microscopic structure in a limestone cannot be relied upon as a proof that the rock is not of organic origin.

The great limestones are almost entirely of marine origin, though quite extensive fresh-water limestones are known. The chemically formed ones are never very widely extended, though they may form quite thick masses. As a rule, the limestones are deposited in deeper water than the sandstones and shales, but not necessarily so, freedom from large amounts of terrigenous sediments being more important than depth of water. This is shown by the great calcareous banks of the Gulf of Mexico and the Caribbean Sea (p. 172), and coral reefs are always formed in shallow water of less than twenty fathoms in depth.

The classification of the limestones is very difficult, and cannot be readily made on any single principle; mode of formation, purity, texture, and nature of organic material, all being employed for the purpose.

Shell Marl is an incoherent and crumbling rock, formed, principally, at the bottom of fresh-water lakes and ponds, by the accumulation of shells; it frequently occurs beneath peat bogs, and is an indication that the bog arose from the choking up of a lake by vegetable growth. When the shells are cemented into a hard rock they form a *fresh-water limestone.*

Chalk is a soft limestone of friable, earthy texture, and frequently very pure; in colour it may be snowy white, pale grey, or buff. The microscope reveals the fact that chalk is principally composed of the shells of Foraminifera, and closely resembles the foraminiferal oozes forming to-day at the bottom of the sea (p. 176). A chalky deposit may, however, be formed from the débris of corals ground up by the waves.

Hydraulic Limestone contains a considerable quantity of clay, and the mortar made from it has the property of setting under water, so that it is used in the manufacture of hydraulic cement.

The ordinary massive marine limestones are named from the character of the organic material which predominates in them. Thus, we have *coral limestone*, *foraminiferal limestone*, made up of the shells of very large extinct forms of the Foraminifera (Fusulina, Nummulites, Orbitolites, etc.), *crinoidal limestone*, *shell limestone*, and the like.

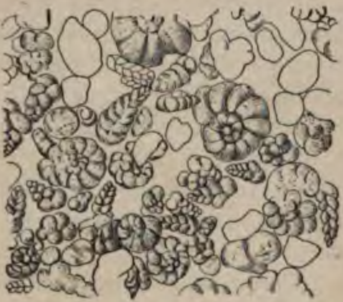


FIG. 76.—Chalk from Kansas. × 45. (Drawn from a photograph by the Geological Survey of Iowa.)

Though much the larger part of the limestones is of animal origin, yet certain seaweeds contribute extensively to formation of these rocks, and there is much reason to believe that chemical precipitation is of greater or less importance in nearly all varieties of the rock.

Dolomite, or **Magnesian Limestone,** is a compact, granular rock of white, grey, or yellow colour, composed of the carbonates of lime and magnesia. Nearly all limestones contain some carbonate of magnesia, but the name *dolomite* is given only to those with a considerable percentage of that substance (5 to 20%). How far this rock is made up of the mineral dolomite, and how far it is merely a mixture of the two carbonates, is uncertain, as is also the way in which the rock was formed. Dolomite contains a much larger proportion of magnesia than the shells or tests of any known animals, and this ingredient must therefore have been added after the accumulation of the calcareous organisms. Opinions differ as to just how this has been accomplished, but probably the magnesia has been derived from the strong brine of lagoons and salt lakes.

The frequent association of dolomite with gypsum gives additional probability to this view. A similar process has been observed in the lagoons of coral reefs at the present time (p. 170), and it has been shown that dolomitization takes place much more readily when the $CaCO_3$ is in the form of aragonite, as is the case in the shells and tests of many marine animals.

Green Sand is not strictly a calcareous deposit, but has a natural connection with that series of rocks. Green sand is seen by the microscope to be largely composed of internal casts of foraminiferal shells in the mineral glauconite (p. 22). The dead foraminiferal shells which lie upon certain areas of the ocean floor are gradually filled up with glauconite, and then the shells are dissolved, leaving the grains of the mineral, which retain the form into which they were moulded. This process is still going on, and has been observed at several points (p. 175).

b. Siliceous Accumulations

The siliceous deposits of organic origin are very much less common and less extensively developed than the calcareous, because of the relatively small amount of silica which is in solution in ordinary waters, and of the comparatively few organisms which secrete shells or tests of it. Nevertheless, these beds are of sufficient importance to require mention.

Infusorial Earth is a fine white powder composed of the microscopic tests, or frustules of the minute plants called diatoms. The fineness and excessive hardness of the particles make this an excellent polishing powder. Beds of this earth occur in both marine and fresh-water deposits. At Richmond, Virginia, is a celebrated deposit of this kind.

Siliceous Oozes are exceedingly rare as rocks of the land; they consist of the tests of Radiolaria, such as are now accumulating in the deeper parts of the ocean (p. 179). The only land areas in which such deposits have been found occur in certain of the West Indian Islands (Barbadoes, Cuba, and others).

Flint or **Chert** occurs in nodules or beds, especially in marine limestones, though it is also found among the sands and clays of certain fresh-water formations, as in Wyoming. Microscopic examination sometimes reveals the presence of sponge spicules and other siliceous organisms, but this is by no means always the case. As we have seen, the structureless cherts are believed to have been formed by chemical precipitation (p. 212).

c. Ferruginous Accumulations

The iron deposits which can be referred to the activity of *living* creatures are of small extent and importance, but certain of the bog-iron ores are believed to be due to the agency of diatoms, which extract the iron from its dissolved state.

d. Carbonaceous Accumulations

The rocks of this group are formed, almost entirely, by the accumulation of vegetable matter and its progressive, though incomplete, decay under water. This decay is of such a nature that the gaseous constituents diminish, while the carbon is removed much less rapidly, consequently the *proportion* of the latter substance steadily rises. All the varieties of carbonaceous rocks pass into one another so gradually, that the distinction between them seems somewhat arbitrary. From fresh and unchanged vegetable matter to the hardest anthracite there is an unbroken series of transitions.

Peat is a partially carbonized mass of vegetable matter, brown or black in colour and showing its vegetable nature on the most superficial examination, though the parts which have been longest macerated are often as homogeneous and as fine grained as clay, and reveal their true nature only under the microscope.

Lignite or **Brown Coal** is a brown or black mass of mineralized and compressed peat, and though still plainly showing its vegetable nature, it does so less obviously than peat, being more carbonized. It is an inferior fuel, though often very valuable in regions where other fuel is scarce or entirely wanting.

Coal is a compact dark brown or black rock, in which vegetable structure cannot be detected by the unassisted eye, though microscopic inspection seldom fails to reveal it. Coal is found in beds or strata, interstratified with shales, sandstones, and, less commonly, limestones. The different kinds of coal vary much in hardness and chemical composition, but they are all connected by intermediate gradations. *Bituminous Coal* has (neglecting the ash) 70 to 75% of carbon and 25 to 30% of volatile matters, chiefly hydrocarbons, which are driven off on destructive distillation. Under the term *bituminous* are included many varieties of coal, which differ much in their behaviour and in their value for different purposes. *Anthracite* is a hard, lustrous coal, that is nearly pure carbon (aside from the ash) and has little or no volatile matter; it burns without smoke or flame and gives an intense heat. *Semibituminous* or *Steam Coal* is intermediate in character and composition between the bituminous and anthracite varieties.

Cannel Coal does not belong in the series of coals above enumerated, but forms a very distinct variety. It occurs in lenticular patches, not in beds, and is very compact, though not very hard or heavy. This coal has from 70 to 85% of carbon and the high proportion of 6 to 7% of hydrogen, giving off large quantities of gas when heated, and burning with a white, candle-like flame. Even with the microscope, it is difficult to detect the vegetable structure of cannel, so thoroughly has the material been macerated. Evidently, cannel is an exceptional coal and has been formed in a somewhat peculiar way. While the ordinary coals evidently represent ancient peat bogs, which by subsidence allowed the sea, or other body of water, to overflow them and were thus sealed up and buried under sedimentary deposits, cannel was formed in pools of clear water, in which vegetable matter was accumulated and very completely disintegrated. This is shown not only by the shape of the coal patches, but also by the fossil fish not infrequently found in cannel.

The following table (from Kemp) displays the composition of the typical varieties of coal, not including the ash: —

	C.	H.	O.	N.
Wood	50	6	43	1
Peat	59	6	33	2
Lignite	69	5.5	25	0.8
Bituminous Coal	82	5	13	0.8
Anthracite	95	2.5	2.5	trace

II. Æolian Rocks

The rocks formed on dry land form very little of the earth's crust, in this respect being altogether insignificant; their importance lies in the hints which they often give as to the physical geography of the place and time of their formation.

Blown Sand is heaped up by the wind into dunes, and displays an irregular kind of stratification. The sand-grains, abraded by their contact with hard substances, are smaller, more rounded, and less angular than the grains of river or even beach sands. If the sand contains any considerable quantity of calcareous matter, the dissolving and redeposition of this by percolating waters will bind the loose material into quite firm rock.

Talus Blocks gather at the foot of cliffs in large masses; these may be cemented into a breccia by calcareous deposits, or, by subsidence, may be buried in marine deposits.

Soil. — In Chapter IV it was shown that soil is mainly the residual product left by the atmospheric decay of rocks, and that its surface layers contain more or less organic matter and are filled with the roots of plants. Soils may be buried under aqueous deposits by floods, or by subsidence marine deposits may be built up upon the soils, which are then interstratified with marine rocks. Ancient soils have been frequently preserved in this manner, filled with fossil roots, and sometimes with the stumps of trees still standing upon them.

In logical order, the Metamorphic Rocks would next come up for consideration; but since we have, as yet, learned nothing of the processes by which these rocks are formed, it will be best to defer the study of this class to a future chapter, when the rocks and their mode of formation will be examined together.

CHAPTER XII

THE STRUCTURE OF ROCK MASSES—STRATIFIED ROCKS

In the preceding chapter we have studied the rocks which make up the crust of the earth, so far as that is accessible to observation. It remains for us to inquire how these rocks are arranged on a large scale, and to what displacements and dislocations they have been subjected since the time of their formation. Examined with reference to the simplest and broadest facts of structure, we find that rock masses fall into two categories: (1) *Stratified Rocks*, and (2) *Unstratified* or *Massive Rocks*. A very brief examination will show us that these two categories correspond respectively to the sedimentary and igneous divisions of the classification according to mode of origin, neglecting, for the present, the metamorphic class.

We shall begin our study of rock masses with the stratified series, because their structure and mode of occurrence are, on the whole, the simplest and most intelligible, and tell their own story. The unstratified series, on the other hand, can be understood only by determining their relation to the former.

The stratified rocks form more than nine-tenths of the earth's surface, and if the entire series of them were present at any one place, they would have a maximum thickness of about thirty miles, but no such place is known. The regions of greatest sedimentary accumulation are the shallower parts of the oceans, while those regions which have remained as dry land, through long ages, have not only had no important additions to their surfaces, but have lost immense thicknesses of rock through denudation. The great oceanic abysses are also areas of excessively slow sedimentation, and thus the thickness of the stratified rocks varies much from point to point, a variation which has been increased by the irregularities of upheaval and depression and of different rates of denudation. Even with this irregularity in the formation and removal of the stratified rocks, it would be exceedingly difficult, if not impossible, to investigate the entire series of them, if they had all retained the original horizontal positions in which they were first laid down. In many places, however, the rocks have been steeply tilted and then truncated by erosion, so that their *edges* form the surface of the ground, and thus great thicknesses of them may be examined without descending below the surface.

Stratification, or division into layers, is the most persistent and conspicuous characteristic of the sedimentary rocks. In studying the sedimentary deposits of the present day (Chapter VIII) we learned that by the sorting power of water, the heterogeneous material brought from the land is arranged into more or less homogeneous beds, separated from one another by distinct planes of division, and the same thing is true of the sedimentary rocks of all ages. This division into more or less parallel layers is called *stratification*, and the extent to which the division is carried varies according to circumstances.

A single member, or bed, of a stratified rock, whether thick or thin, is called a *layer*, though for purposes of distinction, excessively thin layers are called *laminæ*. Each layer or lamina represents an uninterrupted deposition of material, while the divisions between them, or bedding planes, are due to longer or shorter pauses in the process. A *stratum* is the collection of layers of the same mineral substance, which occur together and may consist of one or many layers. However, the term is not always employed in just this sense and often means the same as layer. The passage from one stratum to another is generally abrupt and indicates a change in the circumstances of deposition, either in the depth of water, or in the character of the material brought to a given spot, or in both. So long as conditions remain the same, the same kind of material will accumulate over a given area, and thus immense thicknesses of similar material may be formed. To keep up such equality of conditions, the depth of water must remain constant, and hence the bottom must subside as rapidly as the sediment accumulates.

Usually, a section of thick rock masses shows continual change of material at different levels. Figure 77 is a section of the rocks in Beaver County, Pennsylvania, in which several different kinds of beds register the changes in the physical geography of that area. At the bottom of the section is a coal seam (No. 1), the consolidated and carbonized vegetable matter which accumulated in an ancient fresh-water swamp. Next came a subsidence of the swamp, allowing water to flow in, in which were laid down shales of different kinds (No. 2). This fine-grained clay rock, in this particular instance, probably represents quiet, sheltered water, rather than any considerable depth of it. The accumulations of mud eventually shoaled the water and enabled a second peat swamp to establish itself; this is registered in the second coal bed (No. 3), the thinness of which indicates that the second swamp did not last so long as the first. Renewed subsidence again restored marine conditions, as is shown by the layer of crinoidal limestone (No. 4) which overlies the second coal bed. This depression produced a greater depth of water, and the distance from land was sufficient to prevent the influx of terrigenous sediment. Next, the water was shoaled by an upheaval, and argillaceous sands were laid down, which now form the flaggy sandstones (No. 5) overlying the limestone. The twenty-five feet of sandstone, aided by the continued slow rise of the sea-bottom, silted up the water and allowed a third peat bog to grow, the result of which is the third coal seam (No. 6), while a repetition of the subsidence once more brought in the water, in which were laid down the seventy feet of gravel at the top of the section. In this fashion the succession of strata records the changes of land and sea which were in progress while those strata were forming.

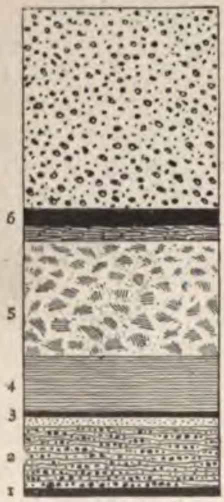


FIG. 77.—Section in coal measures of western Pennsylvania. (White.)

Somewhat similar changes in the strata may be occasioned by the steady lowering of a land surface through denudation. This diminishes the velocity of the streams, which, in its turn, changes the character of the materials which the rivers bring to the sea.

We have no trustworthy means of judging how long a time was required for the formation of any given stratum or series of strata, but it is clear that different kinds of beds accumulate at very different rates. The coarser materials, like conglomerates and sandstones, were piled up much more rapidly than the shales and limestones; so that equal thicknesses of different kinds of strata imply great differences in the time required to form them. Comparing like strata with like, we may say that the thickness of a group of rocks is a rough measure of the time involved in their formation, and that very thick masses imply a very long lapse of time, but we cannot infer the number of years or centuries or millennia required.

Geological chronology can be relative only. Such a relative chronology is given in the section that we have examined by the order of succession of the beds. Obviously the lowest stratum is the oldest and the one at the top the newest. This may be put as a general principle, that, unless strata have lost their original position through disturbance or dislocation, their order of superposition is their order of relative age. It is for this reason that in geological sections the strata are numbered and read from below upward.

Change in the character of the strata takes place not only vertically, but also horizontally, since no stratum is universal, even for a single continent. Our study of the processes of sedimentation which are now at work, showed us that the character of the bottom in the ocean or in lakes is subject to frequent changes, varying with the depth of water and other factors. The same is true of the ancient sea and lake bottoms, now represented by the stratified rocks of the land. Strata may persist with great evenness and uniform thickness over vast areas, and in such cases the bedding planes remain sensibly parallel. But sooner or later, the beds, whenever they can be traced far enough, are found to thin out to

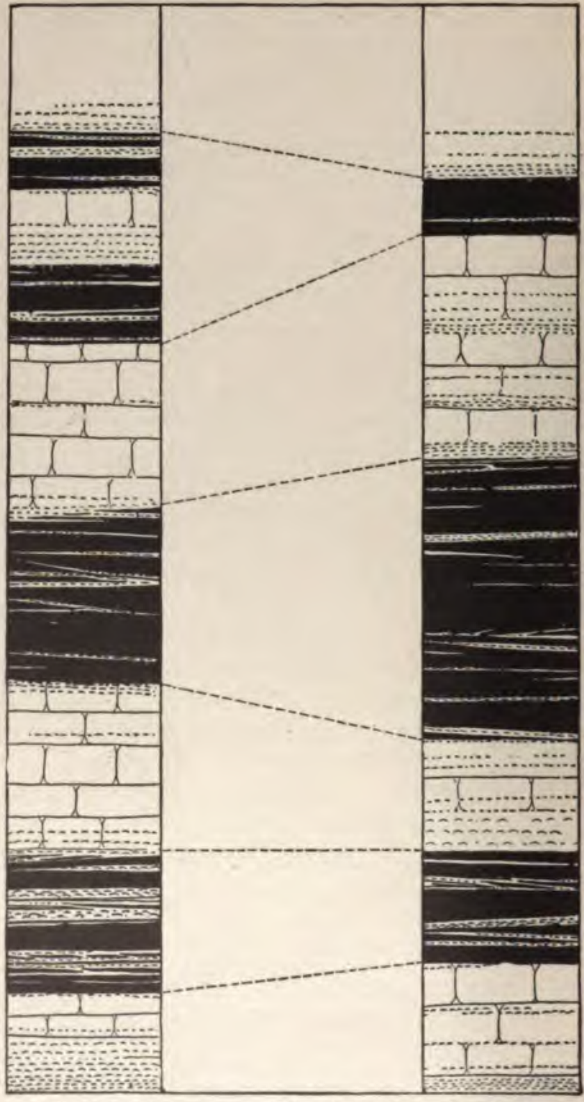


FIG. 78. — Sections near Colorado Springs. (Hayden.)

edges and to dovetail in with beds of a different character. When the strata are of constant thickness for considerable distances, and the bedding planes remain parallel, the stratification is said to be *regular*. In many cases these changes take place rapidly from point to point, and then the strata are plainly of *lenticular* shape, thickest in the middle, thinning quickly to the edges. Here the bedding planes are distinctly not parallel, and the stratification is *irregular*.

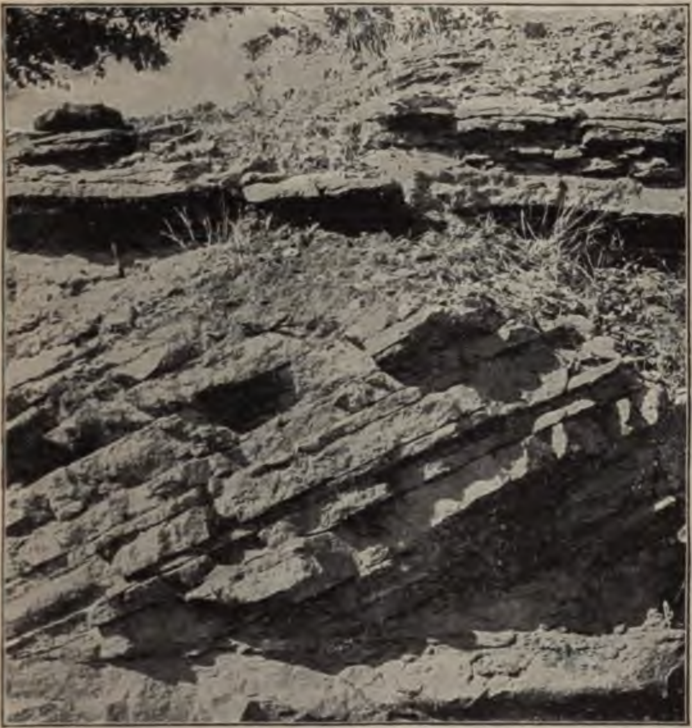


FIG. 79.—Cross-bedded sandstone. (Photograph by the Iowa Geological Survey.)

An example of rapid horizontal changes is given in the two accompanying parallel sections (Fig. 78), taken through the same beds, only twenty feet apart. In these sections the differences of thickness of the coal seams and of the sands and clays which separate them are very striking.

The finer details of structure of the stratified rocks likewise afford valuable testimony as to the circumstances under which the rocks were laid down.

Cross-bedding (also called false or current bedding) is produced by a strong current pushing sediment along the bottom and thus bringing about an oblique lamination, or by the plunge of a wave piling up material in heaps. Cross-bedded layers frequently alternate with horizontally bedded ones, formed in slack water or at ebb tide. Cross-bedding is most common in sandstones, but it may occur in other rocks, even in limestones, though the latter are comparatively seldom accumulated in such shallow water.

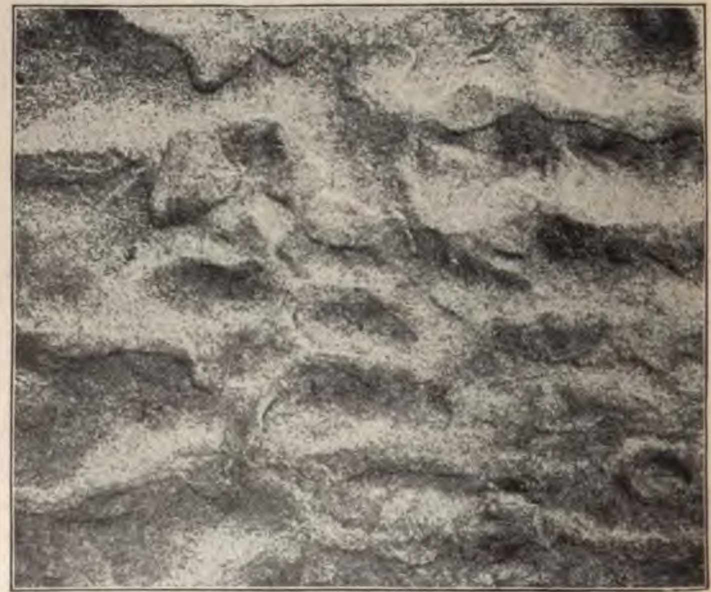


FIG. 80. — Ripple marks on a modern sea-beach. (U. S. G. S.)

Wind Drift is characteristically different from cross-bedding; here the laminæ form all sorts of angles with one another. The lamination is parallel to the surface as that was at the time each lamina was formed; but the sand ridges and dunes are continually changing their shape, as the force and direction of the wind vary, and thus a very complex arrangement results.

Ripple Marks, exactly like those on any sandy beach of the present, are found in rocks of almost all geological dates. Such marks are formed by the wind or by the rippling movement of shoal water. Ripple marks are most frequent and best shown in sandstones, but other rocks, such as shales, often exhibit them also.

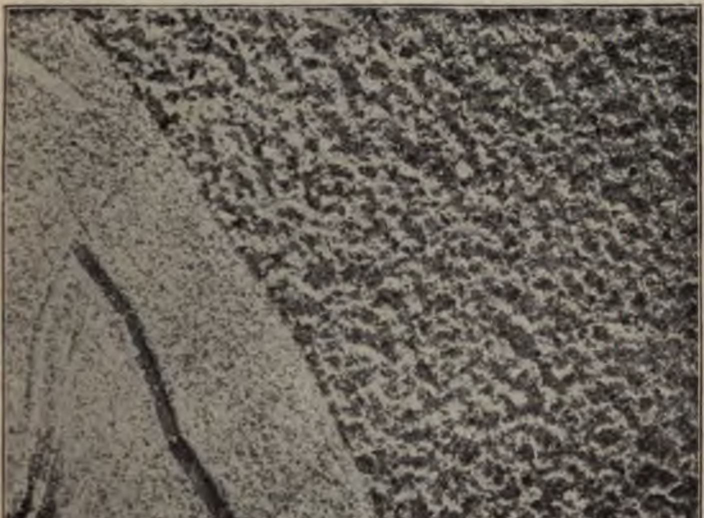


FIG. 81. — Wave mark and rain prints, modern sandy beach. (U. S. G. S.)

Wave Marks are formed by waves washing up on the beach after they have broken, and are preserved by the deposit of thin layers of sand on the edges of the waves, and indicate that the rock in which such marks occur was formed on the very beach.

Naturally, they are almost confined to sandstones, for conglomerates are too coarse to retain such markings. Wave markings, ripple marks, and cross-bedding are all indications of very shallow water and of the immediate proximity of the shore.

Rill Marks are made by little rills of water trickling over the sand as the tide goes out.

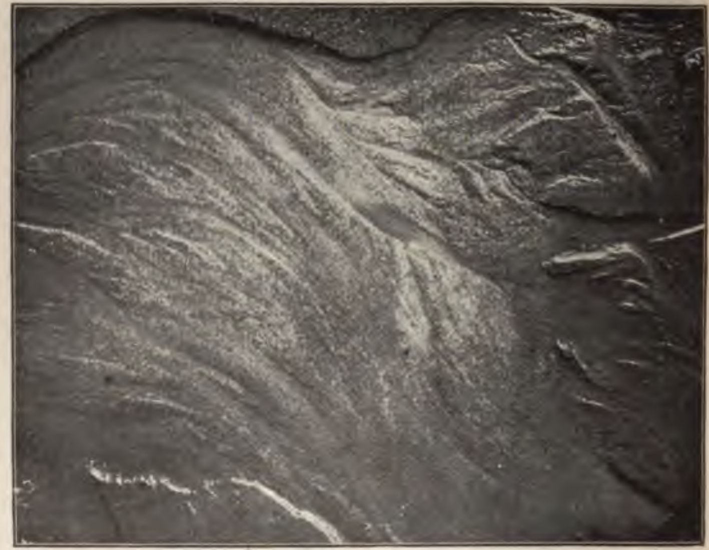


FIG. 82. — Rill marks on modern sandy beach. (U. S. G. S.)

Sun-cracks are produced in mud flats, where the mud and silt, exposed by the retreating tide to the heat of the sun, dry and crack open in more or less regular patterns, a process which may be often observed in drying rain pools. When the incoming tide advances so gently as not to disturb the cracked and hardened surface, but deposits a new layer upon it, filling up the cracks, the latter will be preserved, and on the overlying layer the *casts* of the cracks will stand out in relief, when the two layers are separated. Such marks are common in the fine argillaceous sandstones of the Connecticut valley, New Jersey, and southeastern Pennsylvania.

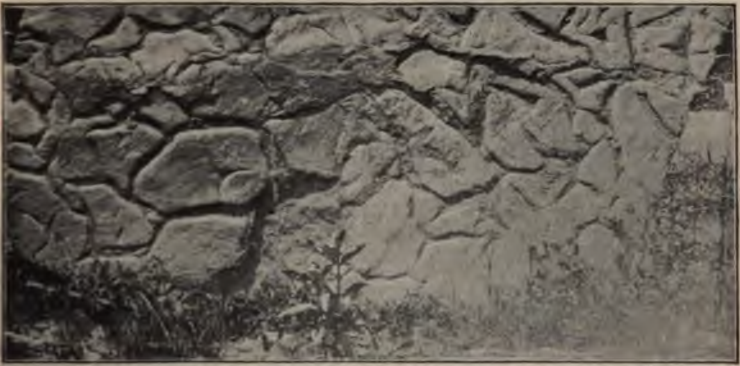


FIG. 83. — Sun-cracks in sandstone. (Photograph by Pynchon.)

Rain Prints are sometimes preserved in fine sand or mud in the same fashion. The raindrops make little pits on the soft surface, which are circular when the drops fall vertically, or oval and with edge raised on one side, when the rain is driven obliquely before the wind. A gentle deposition of fine sediment upon the pitted surface will preserve the marks.

Tracks of Animals are not infrequently found in the strata, and have been preserved in much the same way. Marine animals, such as worms and crustaceans, leave tracks in fine sand, which are covered so gradually and gently by fresh layers that the marks are not disturbed. Tracks of land animals may be preserved when made on the tidal flats of sheltered estuaries, where the surface is somewhat hardened by the exposure to sun and air. On the open sea-beach such tracks would be soon obliterated by the waves.

Marks of this latter class, sun-cracks, rain prints, and tracks of land animals, show that the surface on which they occur was exposed to the air, either periodically by the ebb and flow of the tides, or at stages of low water in rivers and lakes. They are illustrations of the way in which conditions, long passed away, have been recorded for ages in the solid rocks.

Concretions, or *Nodules*, are developed after the formation of strata. They are balls or irregular lumps of material differing

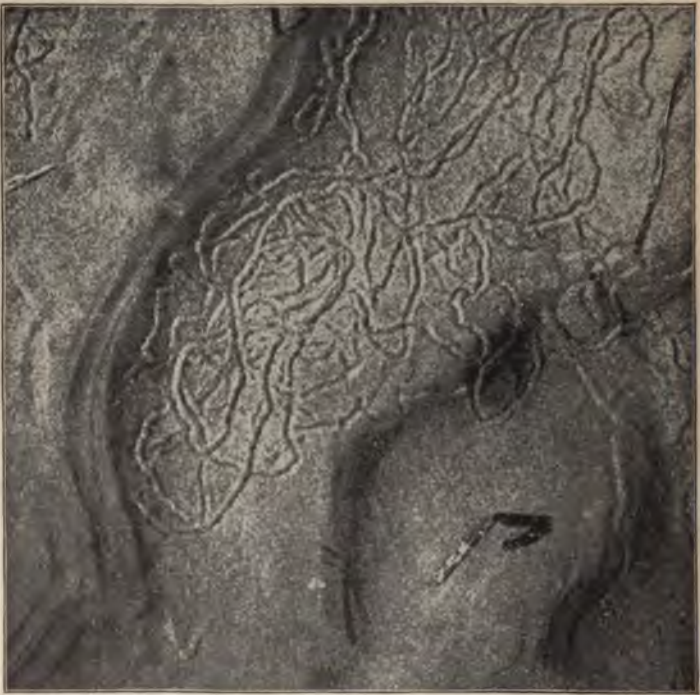


FIG. 84. — Markings by marine worms, modern.

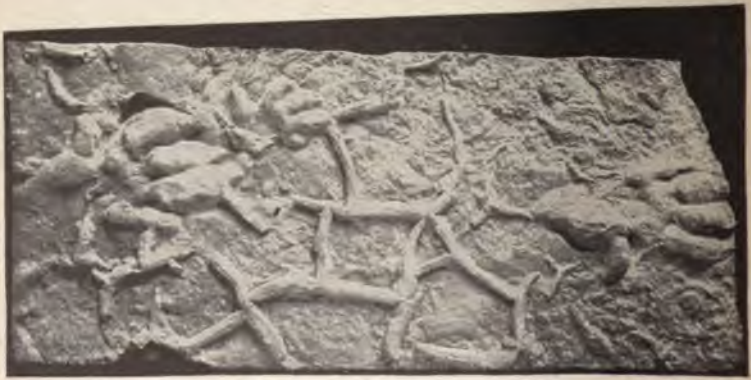


FIG. 85. — Tracks of land animal and sun-cracks, on slab of sandstone.

from that of the stratum in which they occur. They are not pebbles, which are older than the stratum which contains them and which were embedded just as we find them, but are younger than the stratum and were formed subsequently. This is shown by the fact that the planes of stratification may often be traced through the concretion, and that fossils are sometimes found partly within and partly without the nodule. In shape the concretions vary greatly, from almost true spheres, to grotesque aggregations, but always with rounded form, and almost as great a variety of material is found among them. Very often a foreign body, like a fossil shell or leaf, forms the centre or nucleus of the nodule, which has been built up, often in concentric layers, around the nucleus. One form of concretion, known as a *septarium*, is divided internally by radial cracks, which were subsequently filled up with some mineral deposited from solution by percolating waters.

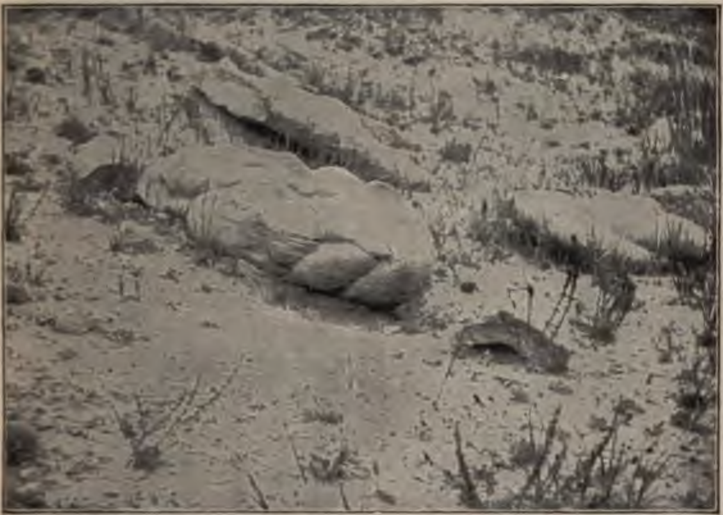


FIG. 86. — Large concretions, weathered out of sandstone, near Fort Buford, Mont. (U. S. G. S.)

The agency which produces concretions cannot as yet be explained. The material of which they are made must have been scattered through the stratum and then gathered together at a later period. Such nodules have been observed in the process of formation in modern sediments, and it has further been noticed that when finely powdered substances are mixed together, certain of them do segregate into lumps. These observations, however, merely confirm the conclusion that concretions are due to segregation of scattered material in the stratum, they give us no explanation of the fact.

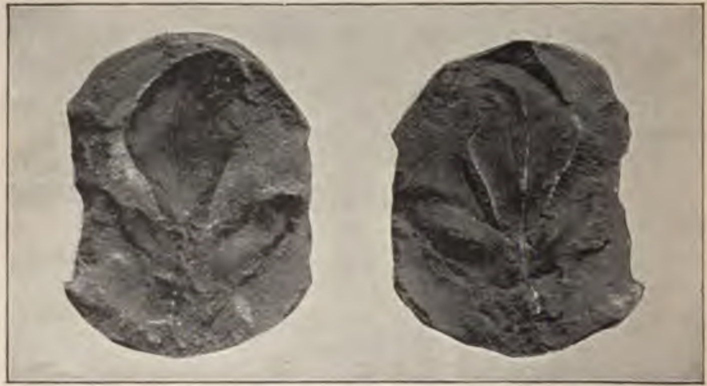


FIG. 87. — Ironstone concretion, split open to show the fossil leaf which forms the nucleus. Mazon Creek, Illinois.

The commonest concretions are those of clay in various kinds of rock, of flint and chert in limestone, and of ironstone in clay rocks.

DISPLACEMENTS OF STRATIFIED ROCKS

It is evident that the stratified rocks which form the land must have been changed, at least relatively, from the position which they originally occupied, since the great bulk of them were laid down under the sea. Originally they must have been nearly horizontal, for this is a necessary result of the operation of gravity. Just as a deep fall of snow, when not drifted by the wind, gradually covers up the minor inequalities of the ground and leaves a level surface, so on the sea-bottom, the sediments are spread out in nearly level layers, disregarding ordinary inequalities. We must remember, however, that this original horizontality is not exact, and departures from it are not infrequent. On a large scale, these departures from the horizontal position are very slight, while those that are conspicuous are always local.

Examples of such original deviations from horizontality are the following: (1) When a sediment-laden stream or current empties abruptly into a deep basin with steeply sloping sides, the sediment is rapidly deposited in oblique layers, which follow the slope of the sides. (2) Alluvial cones, or fans (p. 137), have steeply inclined layers, for a similar reason. Both of these cases resemble the artificial embankments which are built out by dumping earth or gravel over the end, until each successive section is raised to the necessary level. In such embankments the obliquity of the layers is often plainly visible. (3) Sand beaches often have a considerable inclination, as much as 8 %, and newly added layers follow this slope. (4) On a large scale, the great sheets of sediment that cover the sea-bottom generally have a slight inclination away from the land, with a somewhat increased slope along lines of depression. These slight original inclinations of sedimentary masses, either as a whole, or along certain lines, are called *initial dips*, and have an important bearing upon the results of subsequent movements of displacement.

The displacements to which strata have been subjected after their formation are of two principal kinds: (1) In the first kind, the strata have been lifted vertically upward, often to great heights, without losing their horizontality. Over great areas of our Western States and those of the Mississippi valley, the beds are almost as truly horizontal as when they were first laid down. In some of the lofty plateaus through which the Grand Cañon of the Colorado has been cut, almost horizontal strata are found 10,000 feet above the sea-level. (2) More frequent and typical are the displacements of the second class, by which the beds are tilted and inclined at various angles, sometimes bringing the strata into a vertical position, and occasionally even overturning and inverting them. In the comparatively small exposures of strata which may be seen in ordinary sections in cliffs and ravines, the rocks appear to be simply inclined, and the strata themselves to be nearly straight. But when the structure is determined on a large scale, it is found that this appearance is due to the limited area visible in one view, and that the apparently straight beds are really portions of great curves. Such curves are called *folds*.

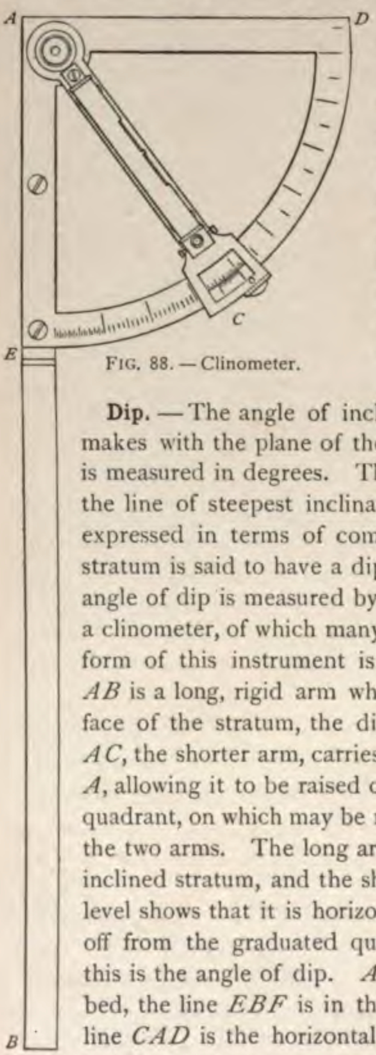


FIG. 88. — Clinometer.

Dip. — The angle of inclination which a tilted stratum makes with the plane of the horizon is called the *dip*, and is measured in degrees. The line or direction of the dip is the line of steepest inclination of the dipping bed, and is expressed in terms of compass bearing. For example, a stratum is said to have a dip of 15° to the northwest. The angle of dip is measured by means of an instrument called a clinometer, of which many kinds are in use. An excellent form of this instrument is shown in the annexed figure. *AB* is a long, rigid arm which is applied to the upper surface of the stratum, the dip of which is to be measured. *AC*, the shorter arm, carries a spirit level, and is pivoted at *A*, allowing it to be raised or lowered. *DE* is a graduated quadrant, on which may be read the angle included between the two arms. The long arm is laid on the surface of the inclined stratum, and the short arm raised, until the spirit level shows that it is horizontal, and the angle is then read off from the graduated quadrant. Figure 89 shows that this is the angle of dip. *AB* is the surface of the dipping bed, the line *EBF* is in the plane of the horizon, and the line *CAD* is the horizontal line of the spirit level, parallel to *EBF*. The angle *DAB* is the one actually measured, but as the two horizontal lines are parallel, that angle must be equal to the angle *ABE*, which is the actual angle of dip.

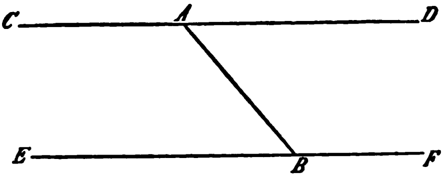


FIG. 89.— Diagram explanatory of dip measurement.

Strike.—The line of intersection formed by the dipping bed with the plane of the horizon is called the line of strike and is necessarily at right angles to the line of dip. (See Fig. 91.) If a piece of slate be held in an inclined position and lowered into a vessel of water, the wet line will represent the strike. As long as the direction of the dip remains constant, the line of strike is straight, but as the direction of the dip changes, the strike changes also, always keeping at right angles to the dip, and in such cases as the Appalachian Mountains the lines of strike are sweeping curves.

Outcrop is the line along which a dipping bed cuts the surface of the ground, and is, of course, due to erosion, which has truncated the folds of strata. Except in the case of fractured beds, which will be considered in the following section, if there were no erosion, there could be no outcrop. When the surface of the ground is level, outcrop and strike become coincident, because the surface then is practically a horizontal plane. With the dip remaining constant, the more rugged and broken the surface becomes, the more widely do strike and outcrop diverge. For a given form of surface, outcrop and strike differ more when the beds dip at a low angle than when the dip is steep, for when the strata are vertical, outcrop and strike again coincide, and the more nearly the strata approach verticality, the more closely do the two lines come together.

Having digressed to make these necessary definitions, we may now return to the subject of folds.

Folds present themselves to observation under many different aspects, all of which may be regarded as modifications of two principal types.

(1) The *Anticline* is an upward fold or arch of strata, from the summit of which the beds dip downward on both sides. The curve of the arch may be broad and gentle, or sharp and angular, or anything between the two. The line along which the fold is prolonged is called the *anticlinal axis* and may be scores of miles in length, or only a few feet. This may be illustrated by an ordinary roof, which represents the two sides or limbs of the anticline, while the ridge-pole will represent the anticlinal axis. Whether long or short, the fold eventually dies away, and thus the summit of the arch is not perfectly level, but more or less steeply inclined, and this inclination is called the *pitch* of the fold. In

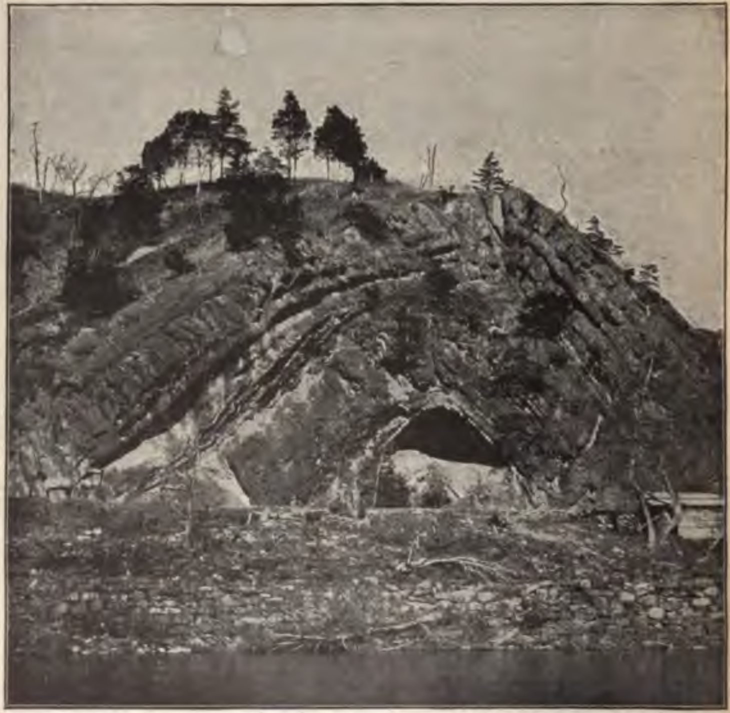


FIG. 90.— Anticline on the Potomac, Maryland. (U. S. G. S.)

accordance with the length of the axis and the steepness of the pitch, the uneroded anticlinal is either short and dome-like, or elongate and cigar-shaped.

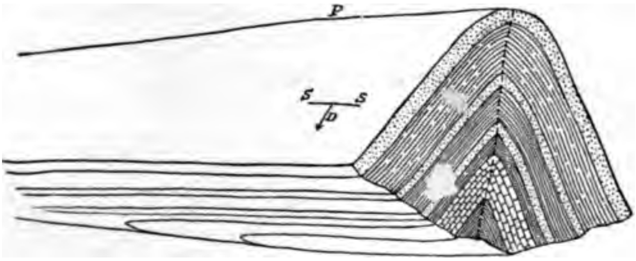


FIG. 91.—Anticlinal limb of fold. *P*, axis pitching to the left; *S S*, line of strike; *D*, line of dip. The dotted line is the plane of the axis. (Willis.)

(2) The *Syncline* is the complement of the anticline, and in this the beds are bent into a downward fold or trough, dipping from both sides toward the bottom of the trough, which forms the longitudinal synclinal axis. As in the anticline, the axis may be long or short, with gentle or steep pitch, forming long, narrow, "canoe-shaped" valleys, or oval, even round, basins. In section the syncline may be shallow and widely open, or with steep sides and angular bottom.

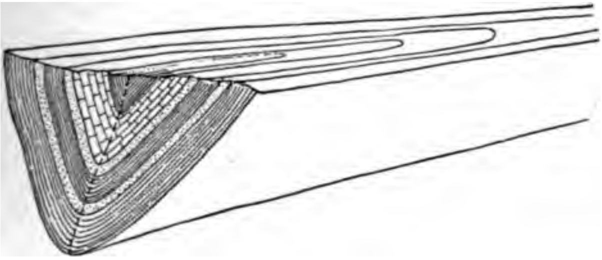


FIG. 92.—Synclinal limb of fold. (Willis.)

Domes and *Basins* are special cases of anticlines and synclines. The dome is an anticlinal fold, in which the axis is reduced to zero, the dip of the beds being downward in all directions from the summit of the dome. As the dip changes, the strike changes, describing an oval or circle. Similarly, the basin is a syncline with axis reduced to zero, the beds dipping downward from all sides to the bottom of the basin, and the strike forming the edge of the basin. The term *basin* is used in different senses, and it is necessary to distinguish carefully between a basin of folding and one which has been excavated by erosion.

It is rare to find a single anticline or syncline occurring by itself; very much more frequently they are found in more or less parallel series, each pair of anticlines connected by a syncline. At one end of the system we may find several axes converging and uniting into a single fold, and they all die away sooner or later, the pitch of the folds coinciding with the dip of the beds.

Anticlinorium and *Synclinorium.* — The system of roughly parallel folds which are grouped together may be, when regarded as a whole, either anticlinal, rising up into a great compound arch, or synclinal, depressed into a great compound trough. The former is called an anticlinorium, and the latter a synclinorium. The secondary folds which compose one of these systems may themselves be compound and made up of many subordinate folds, the smallest of which can be detected only with the microscope.

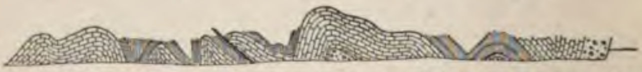


FIG. 93. — Anticlinorium: section through the Appalachian Mountains. (Willis.)

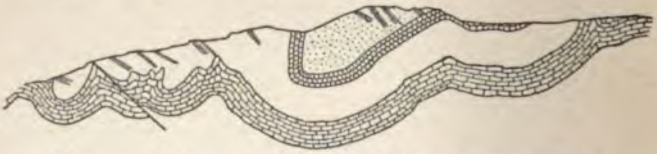


FIG. 94. — Synclinorium, Mt. Greylock, Massachusetts. (Dale.)

Geanticline and *Geosyncline.* — The folds and flexures which we have so far examined are those which affect the strata at the surface or at comparatively moderate depths. It is quite impossible that the whole crust can be involved in folds of such small amplitude. The crust is, however, subject to flexures of its own, which are characterized by their great width and gentle slope. Such flexures have been named by Dana geanticlines and geosynclines, to express their importance for the earth as a whole.

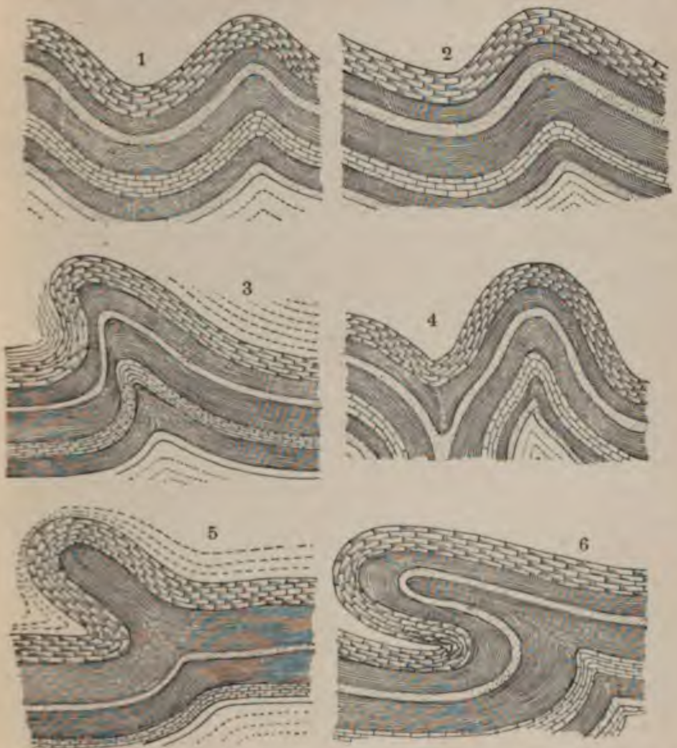


FIG. 95.—Diagrams of folds. (Willis.) 1. Upright or symmetrical open folds. 2. Asymmetrical fold, open. 3. Asymmetrical fold, closed and overturned. 4. Symmetrical fold, closed. 5. Closed anticline, overturned. 6. Closed anticline, recumbent.

The great thickness of sediments which form the Appalachian Mountains (exceeding 30,000 feet) was laid down in an immense geosynclinal trough, which through long ages slowly sank as the sediments accumulated. The rate of subsidence so nearly equalled the rate of deposition, that almost the entire thickness was accumulated in shallow water, as is indicated by the character of the rocks themselves. Geanticlines are less easy to detect, but there is evidence to show that they do occur on an equally great scale.

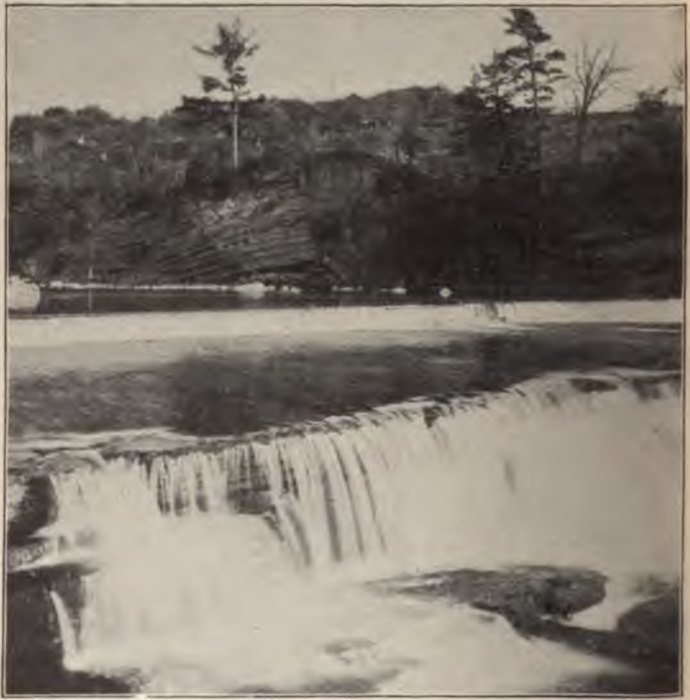


FIG. 96. — Asymmetrical open fold. High Falls, Ulster County, N.Y. (U. S. G. S.)

Folds may be classified either in accordance with the relation which their opposite limbs bear to each other, or with reference to the degree of compression to which they have been subjected. Using the first method, we may distinguish the following varieties.

Upright or *Symmetrical.* — In this case the two limbs of the fold dip at the same angle, the plane of the axis of the flexure is vertical and bisects the fold into equal halves. In *asymmetrical*, or *inclined*, folds the opposite limbs have different angles of dip, the axial plane is oblique and divides the flexure into more or less dissimilar parts. When one limb has been pushed over past the perpendicular, the fold is said to be *overturned* or *inverted*, and when this has gone so far that one of the limbs becomes nearly or quite horizontal, the fold is *recumbent*.

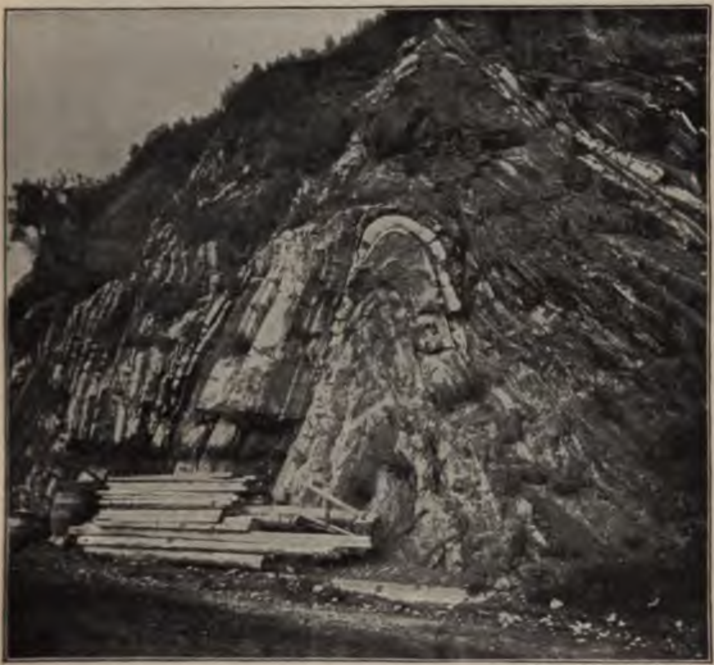


FIG. 97.—Symmetrical, closed anticline: near Quebec, Canada. (U. S. G. S.)

According to the second mode of classification, we have a somewhat different series of terms; but both methods have their uses and must be employed. *Open folds* are those in which the limbs are widely separated; strata with open, gentle flexures are said to be *undulating*. *Closed folds* are those in which the limbs of the flexures are in contact and any further compression must be relieved by a thinning of the beds. *Contorted* strata are thrown into closed folds, which are connected by sharp, angular turns. *Plications* are intense crumplings and corrugations of the strata.

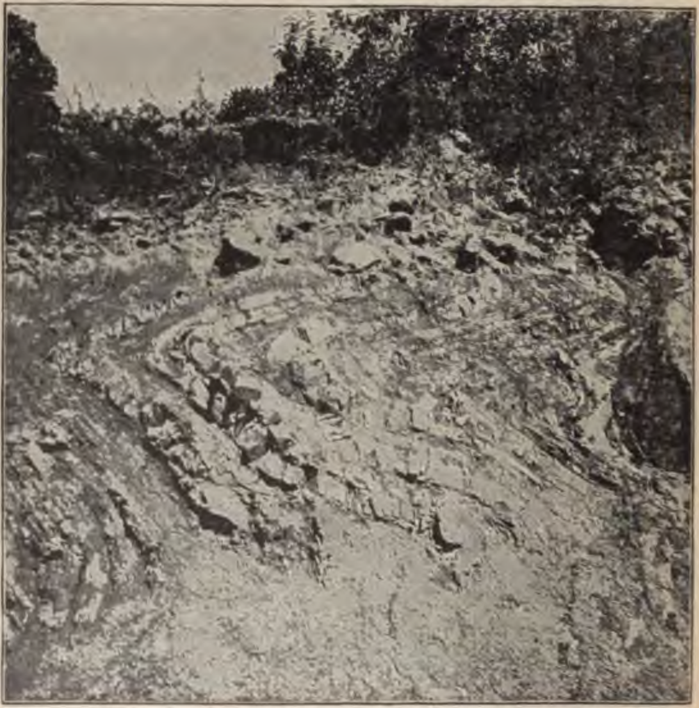


FIG. 98.—Closed recumbent folds, Doe River, Tennessee. (U. S. G. S.)

Isoclinal folds are those which have been so bent back on themselves that the limbs of the flexures are all parallel, or nearly so. When a series of isoclines has been planed down by erosion to a level, the strata show a continuous, uniform dip and present a deceptive appearance of being a simple, tilted succession of beds. A still further compression of isoclinal folds produces *fan folds*. In this structure the anticlinal is broader at the summit than at the base and the synclinal broader below than above, a reversal of the normal arrangement.

The isoclinal and fan folds may be upright, inclined, inverted, or recumbent. In the closed folds there has been such enormous compression that the same strata are of different thickness in different parts of the flexure. This is especially marked in fan folding, in which the beds are much thinner on the limbs than at the summit, and sometimes the central beds in the folds have been actually forced to flow upward or downward, forming isolated masses, cut off from their original connections.

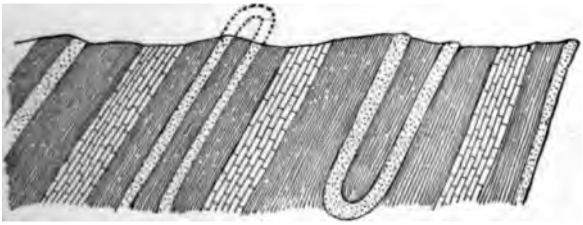


FIG. 99. — Inclined isoclinal folds, eroded. (Willis.)

Besides the simple folds above described, there are frequently found complex systems of flexures, in which the compressing force has acted simultaneously or successively in different directions, producing highly complicated cross-folds. These are, however,

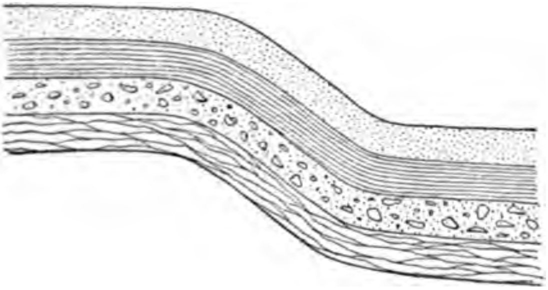


FIG. 100. — Diagram of monoclinal fold.

often extremely difficult to work out, and in an elementary book, intended for the beginner, it is not necessary to do more than mention them.

The *monoclinal fold* is a somewhat exceptional type, which can hardly be regarded as a modified form of the anticline. A monoclinal flexure is a single, sharp bend connecting strata which lie at different levels and are often horizontal except along the line of flexure. Folds of this character are very common in many parts of the West, especially in the high plateau region of Utah and Arizona.

CHAPTER XIII

DISLOCATIONS AND FRACTURES OF STRATA

STRATA are often unable to accommodate themselves by bending or plastic flow to the stresses to which they are subjected; and instead of flexing they are fractured, usually accompanied by more or less dislocation. A simple crack or fracture through the strata, not involving dislocation, is called a *fissure*. On the two sides of a fissure the beds are the same at corresponding levels, and evidently the crack has been made through continuous strata.

Faults. — When the strata on one side of a fissure have been lifted up or dropped down, so that the strata which were once continuous across the plane of fracture are now separated by a greater or less vertical interval, and lie at different levels, the structure is called a *fault*. A fault is sometimes, but not very often, vertical; usually it is inclined at a greater or less angle, and the angle made by the intersection of the fault plane with a vertical plane is called the *hade* or *slope* of the fault. The *fault dip* is the angle included between the fault plane and a horizontal plane, and is the complement of the hade. For example, if the fault is vertical, the hade is 0° and the dip 90°; if the fault is horizontal, the hade is 90° and the dip is 0°, while a hade of 45° gives a dip of the same amount. The side on which the beds lie at a higher level than their continuations across the fracture is called the *upthrow side*, and the other is the *downthrow side*. Owing to the obliquity of the fault plane, the beds on one side usually project over those on the other, and hence form the *hanging wall;* that side which extends underneath the other is called the *foot wall*. Either the foot or the hanging wall may be the upthrow or downthrow side, according to the nature of the fault. The friction of the rocks grinding against each other in the fault frequently smooths and polishes them, which gives the characteristic appearance known as *slickensides*.

The movements of the beds along the fault plane are usually simple, and in only one direction, but there are several different kinds of measurements to be taken, which express important facts. The amount of vertical displacement between the two fractured ends of a given stratum is called the *throw* ($b'c$, Fig. 101), and the *heave*, or *horizontal throw*, is the horizontal distance through which one end of a fractured stratum has been carried past the corresponding end on the other side of the fault plane (bc, Fig. 101). The heave of a fault increases in proportion to the throw, as the hade increases. In a vertical fault, which has no hade, there is no heave, however great the throw; for in that case the fractured ends of the strata are not carried past each other horizontally, and the throw of the fault is measured along the fault plane. With the amount of throw remaining constant,

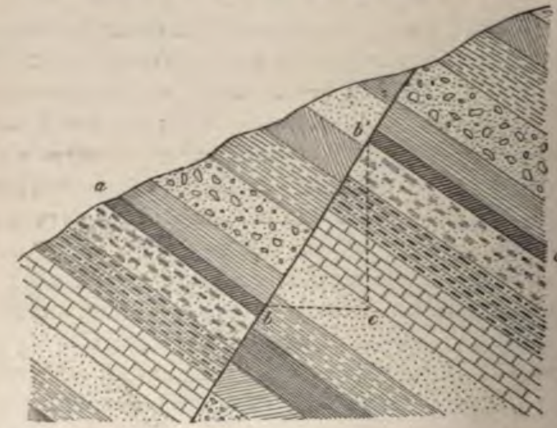


FIG. 101.—Section through faulted beds. $b'c$, throw; bc, heave; bb', stratigraphic throw, which in this case is measured along the fault plane, because the latter happens to be at right angles to the bedding planes. The angle $bb'c$ is the angle of hade; $b'bc$, the angle of dip. Foot wall to the right of the fault, and hanging wall to the left.

the heave increases with the hade. The *stratigraphic throw* is the thickness of beds which intervenes between the broken ends of a fractured stratum (*i.e.* on opposite sides of the fault), and is measured at right angles to the bedding planes. When the

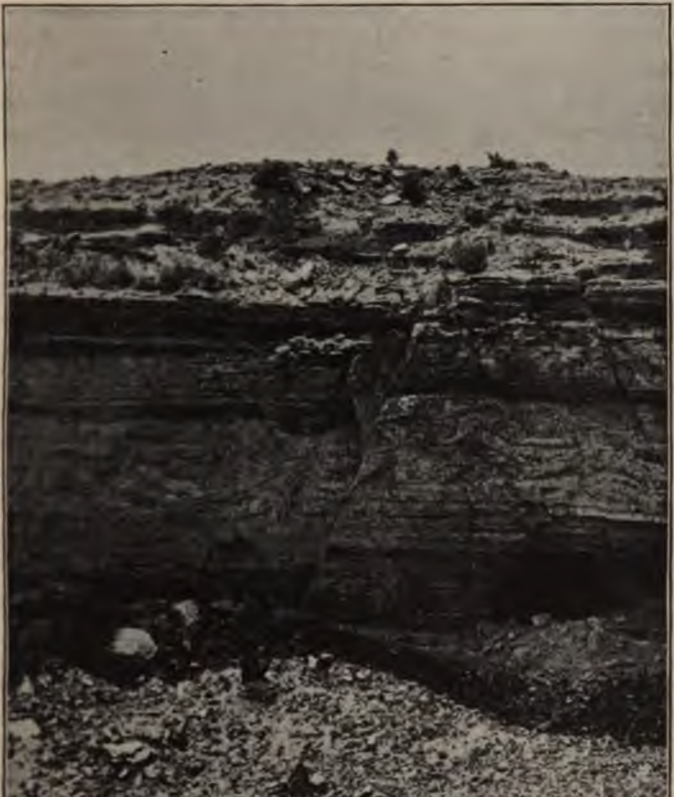


FIG. 102. — Normal fault of small throw in horizontal strata: fault scarp removed by denudation. (U. S. G. S.)

faulted strata are horizontal, the vertical throw is the same as the stratigraphic, but if the strata are inclined, the two differ.

Though the term *fault* is applied to any dislocation of strata, by which the broken ends of the beds are carried over or past each other, yet it includes structures of very different significance, produced in dissimilar ways. Of these there are two principal classes: —

I. **Normal, or Gravity, Faults** (Figs. 101, 102) are those in which the hade is toward the downthrow, or depressed side, and thus the hanging wall is on the latter side, while the foot wall forms the upthrow side. The phrase "normal fault" is an unfortunate one, but it seems to be too deeply fixed in geological usage for any change to be practicable. Faults of this class ordinarily occur in horizontal or moderately inclined or folded rocks. As will be seen in a later section, normal faults in horizontal or gently inclined strata imply the extension of an arc of the earth's crust, because the faulted beds occupy more space, horizontally, than they did before dislocation. They are therefore due to a *tension* greater than the rocks could endure.

The normal faults of any district may nearly always be classed in two categories: (1) *Strike faults*, which, in general, follow the strike of the beds. To this group belong the great faults, — great both as to length and amount of displacement. (2) *Dip faults*. These are more or less parallel to the dip of the strata, and therefore form an open angle with the strike faults of the same area; they are less important than the latter.

The amount of displacement of faults varies greatly in different cases, from a fraction of an inch up to thousands of feet. In those of small throw the fault plane is frequently a clean, sharp break; but in the greater faults the rocks in the neighbourhood of the fault plane are often bent, crushed, and broken. The fault itself is then filled up with a confused mass of fragments of all sizes, which may be cemented into a breccia. Such a mass is called *fault rock*. In soft rocks the fault plane is always closed by the immense weights and pressures involved, but in rigid rocks it may remain more or less open, especially if the break be not a true plane, but of curved and irregular course. In the latter case, there will be a succession of cavities along the fault, which frequently are filled up by a subsequent deposit of minerals, and thus converted into mineral veins.

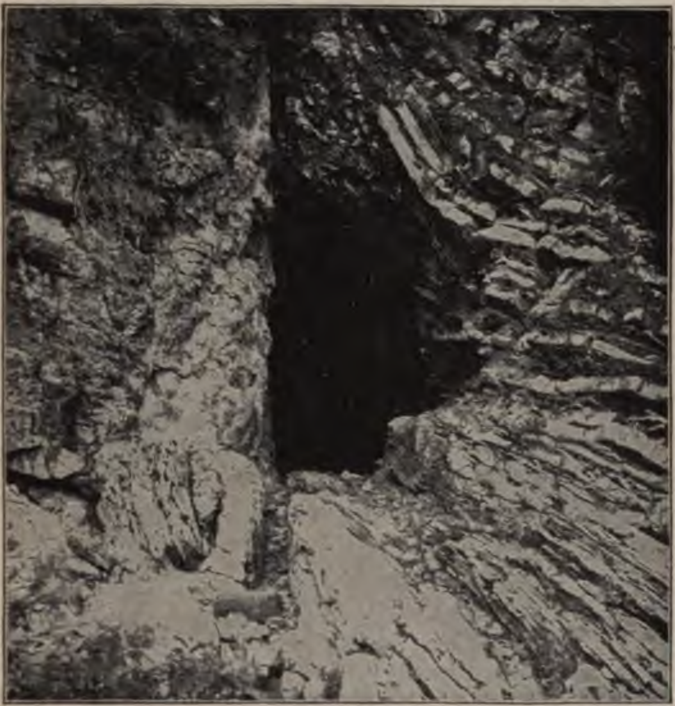


FIG. 103.—Strata bent upward near the fault plane. The hole is artificial. (U. S. G. S.)

Faults may die out in a few yards, or they may run for hundreds of miles; they may be simple or compound, single or branching. A *compound fault* is made up of a number of parallel dislocations, placed close together, which may all hade in the same direction, or in opposite ways, but in the latter case one hade prevails over the other. A series of parallel faults, wider apart than in the compound faults, and all hading in the same direction, are called *step faults*. If two parallel dislocations hade toward each other, they form a *trough fault* and include a wedge-shaped *fault block* between them, which is on the downthrow side of both dislocations.

However long it may be, a fault sooner or later dies away, the throw constantly diminishing toward the ends, until it vanishes. This implies that the fault is due to the bending of the beds upward or downward along the plane of dislocation; only three intersecting or two curved faults can actually isolate a fault block. Intersecting or *cross faults* may be of very different dates, and then the more ancient ones can be determined by the fact that they are themselves dislocated.

It is comparatively seldom that the upthrow side of a fault is left standing as a line of cliffs; when such is the case, the cliffs form a *fault scarp*, many of which may be found in the more arid districts of the West, where atmospheric erosion has been slow. In the great majority of instances, the upthrow side suffers more rapid denudation than the downthrow, and the two are weathered down to approximately the same level, or the same general slope (see Figs. 102, 105). Under these circumstances, faults are rarely visible on the surface, and their presence must be inferred indirectly from their effects upon the outcrops of the strata involved. These

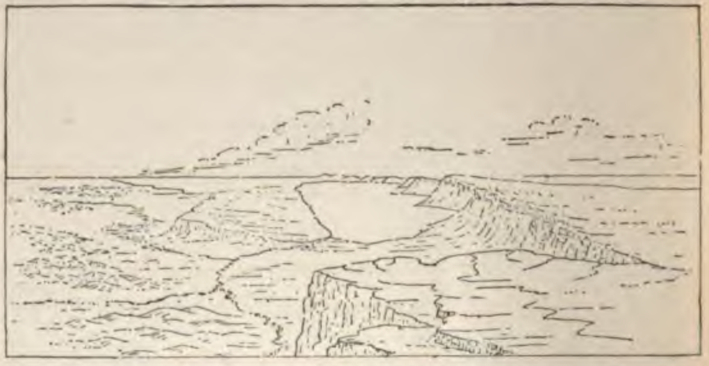


FIG. 104.—Abert Lake, Oregon. The line of cliffs is a fault scarp. (Russell.)

effects depend upon the direction and throw of the fault and upon the inclination of the beds. Strike faults repeat the outcrops, bringing the beds again to the surface; in a series of parallel or step faults, a given stratum has a number of outcrops greater by one than the number of faults. This repetition of the outcrop may be very deceptive, when the surface has been planed down to one uniform slope or curve. In Fig. 106, for example, the observer might easily be misled into believing that seven seams of coal were cropping out on the hillside, whereas the section shows that there are only two such seams, their repeated outcrops being due to faulting.

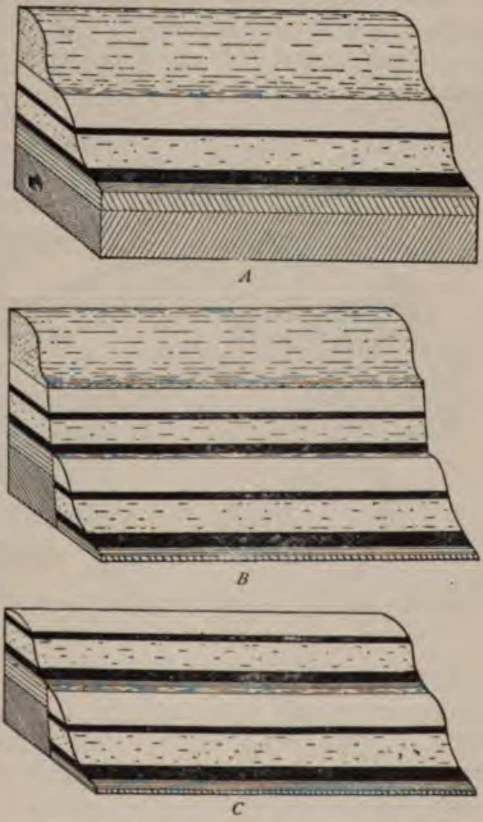


FIG. 105.—Effect of strike fault on outcrop. *A*, before faulting; *B*, with fault scarp standing; *C*, with both upthrow and downthrow sides denuded to a continuous curve. (Drawn from a model by Sopwith.)

The repetitions of outcrop, such as have been described, occur when the throw, or amount of displacement, is moderate. Great faults, displaced many thousands of feet, and with the upthrow side planed away by denudation, will display entirely different strata on the two sides of the fault. The deep-seated beds, which, on the upthrow side, are exposed by denudation, are, on the downthrow side, carried down so far, that they do not reach the surface at all, or, at least, not in the neighbourhood of the fault. Also, if the hade of the fault is in the same direction as the dip of the strata, repetition of outcrop may fail to occur.

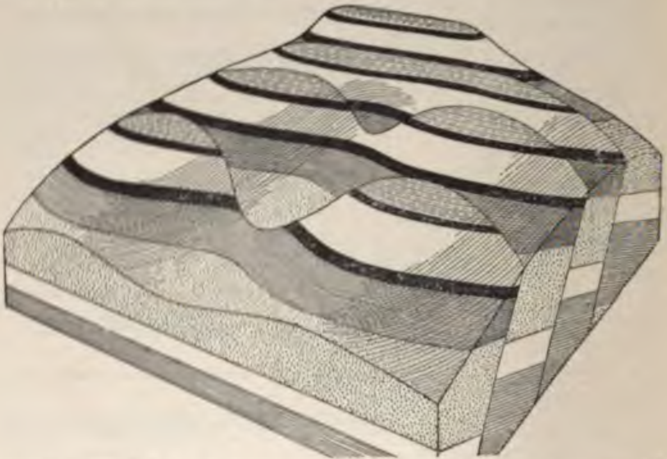


FIG. 106.—Effect of step faults in repeating outcrops. (Drawn from a model by Sopwith.)

Dip faults have entirely different effects upon the outcrops from those occasioned by strike faults, cutting across the strike of the beds and interrupting their continuity. The outcrop of a given stratum ceases abruptly at the fault line, and when found on the other side, it is seen to be shifted a greater or less distance in the direction followed by the fault plane. How such a horizontal shifting is brought about by a vertical displacement is shown by the model (Fig. 107). In I the model is shown as it was before faulting, the black band representing a dipping stratum, say a coal seam, seen in section on the side of the model, with the outcrop appearing on its upper surface. In II the dislocation has occurred, the upthrow side still standing as a fault scarp, while III shows this scarp removed by denudation and the two sides planed down to the same level. It is here seen that, on the downthrow side, the outcrop is shifted in a direction opposite to the dip of the beds, or, what amounts to the same thing, on the upthrow side, it is shifted in the direction of the dip. The amount of shifting will evidently increase with the throw of the fault, but diminish as the dip of the beds increases.

When a dip fault cuts across eroded folds, the distance between the outcrops of the same stratum on the two limbs of an anticline is increased on the upthrow side, diminished on the downthrow side; in the synclines this arrangement is reversed. This is because on the upthrow side the surface of the ground cuts the beds at a lower stratigraphic level than on the downthrow, and as the limbs of an anti-

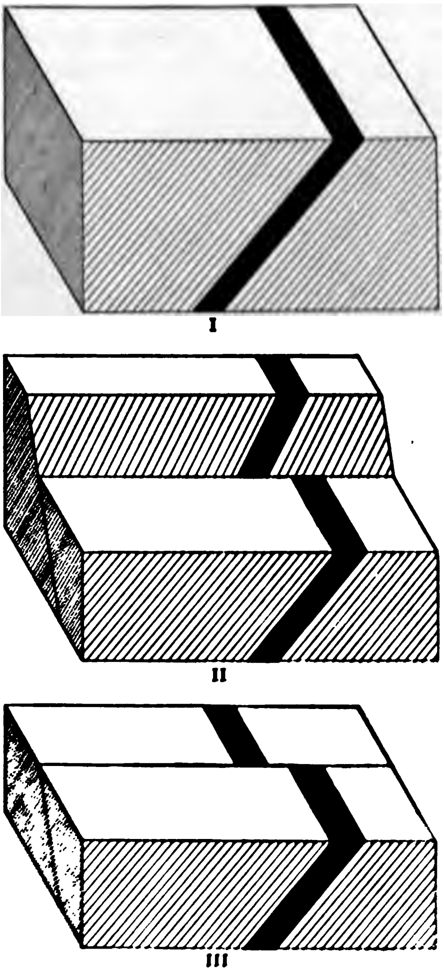


FIG. 107. — Model showing effect of dip fault on outcrop. I, before faulting. II, with fault scarp standing; III, with fault scarp removed by denudation.

cline diverge downward, the outcrops will be more widely separated, the lower the level at which they reach the surface. In a syncline the limbs converge downward, and the effect of the fault is therefore just the reverse of what occurs in the anticline.

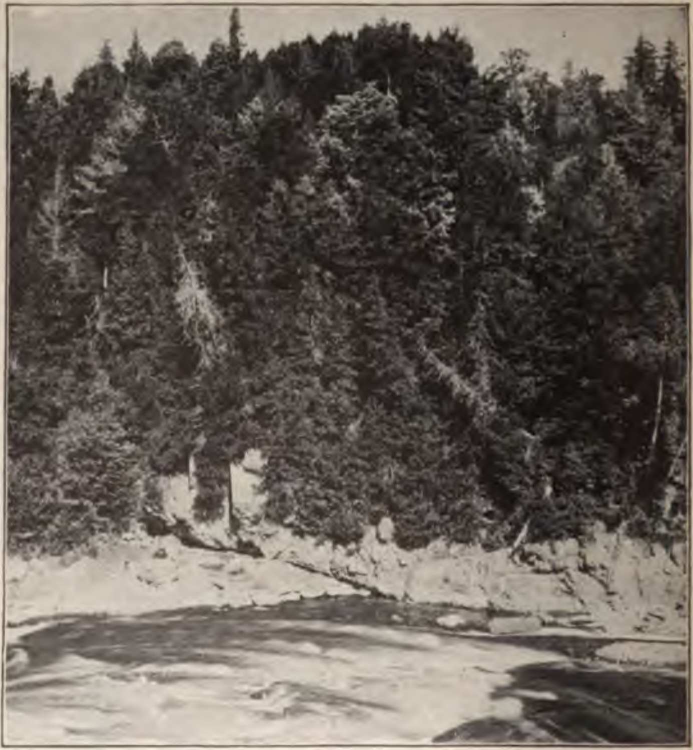


FIG. 108. — Great thrust fault, near Highgate Springs, Vt. (U. S. G. S.)

In an area traversed by normal faults, the beds of the fault blocks which are included between the parallel or intersecting faults are usually not strongly folded. There is, nevertheless, a close connection between faults and flexures, as the examination of any disturbed district will show. Especially is this true of monoclinal folds, which often pass into faults, the beds yielding to flexure along part of their course, fracturing and dislocating in other parts.

II. Reversed or Thrust Faults (also called overthrust faults or simply thrusts).—These are the opposite of the so-called normal faults, the hade being toward the upthrow side, which thus forms the hanging wall, while the downthrow side is the foot wall. Faults of this class are due to compression, the strata breaking and slipping past and over one another, instead of folding, and they are characteristic of highly folded regions, sharp plications often passing into thrust faults. Thrust faults are produced in somewhat different ways, and have, accordingly, been divided by Mr. Willis into four categories.

(1) The *shear thrust*, when the strata are dislocated by compression and carried along a fault plane over other beds; the strata shearing more easily than bending. Thrusts of this character are independent of flexures.

(2) The *break thrust* occurs when the strata are first folded into an anticline and then fractured, the upper limb of the broken fold being pushed forward over the lower.

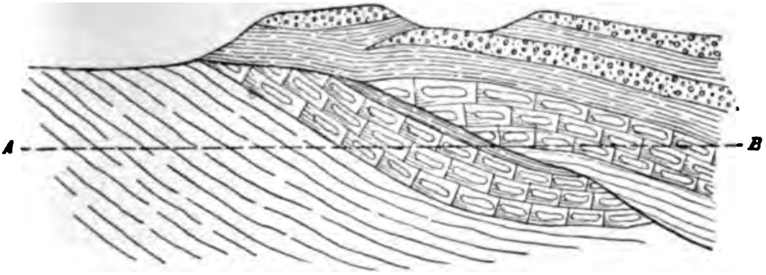


FIG. 109.— Erosion and break thrust, Holly Creek, Georgia. (Hayes.)

(3) The *stretch thrust* is caused by plication and inversion, by means of which the overturned limb is stretched, broken, and dislocated.

(4) The *erosion thrust*. When the outcrop of a rigid stratum on the flank of an anticline is caused by erosion, it will meet with

no resistance when the compressing force is again applied, but will ride forward over the underlying bed.

Thrust (or reversed) faults hade at greater angles (or, in other words, dip at smaller angles) than do the normal ones, and in some of the great thrusts the fault planes are almost horizontal: thrusts are always along the strike, never parallel with the dip. If not of too great throw and heave, thrust faults repeat the outcrop of strata, as do the normal strike faults, but in those of very large displacement, the beds which are brought into close juxtaposition are so widely separated stratigraphically, that no repetition occurs. Faults of this class occur on a grand scale in the Appalachian Mountains, especially in the southern part of that system, and even more notable examples are to be found in the northwestern part of Scotland.

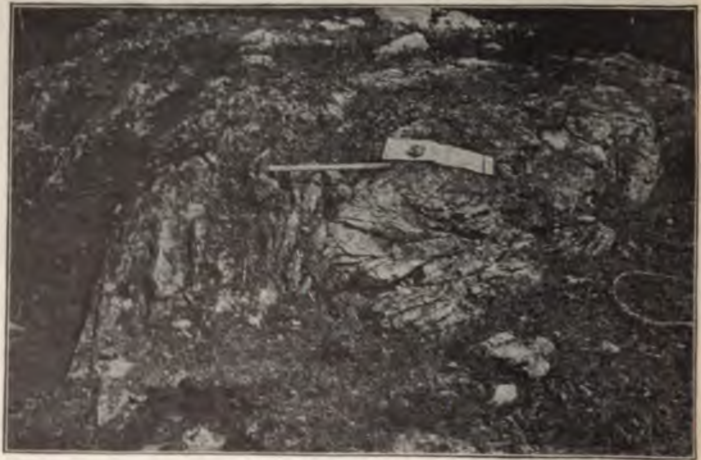


FIG. 110. — Great thrust fault, near Highgate Springs, Vt. The upthrow side has been denuded away and the hammer spans the fault, connecting beds which are stratigraphically many thousands of feet apart. (U. S. G. S.)

THE CAUSES OF FOLDING AND FAULTING

The first step in this inquiry must be to determine the direction in which the folding force acted. It might seem natural, at first sight, to suppose that the direction of the force was vertically upward, acting with maximum intensity beneath the anticlines and with minimum intensity beneath the synclines. But such an explanation could only apply to open, symmetrical, and simple folds, and even in these cases, is not satisfactory. Folded strata must either occupy less space transversely than they did before folding, or else they must have been stretched and made much thinner, but a comparison of continuous beds, in the flexed and horizontal parts of their course, shows no such thinning. Again, such an explanation is obviously insufficient to account for closed, inclined, and inverted folds, for contortions and plications, and for flexures of different orders, one within another.

If the folding force did not act vertically, it must have acted horizontally, and this is the explanation now almost universally accepted. A horizontally acting force would compress and crumple up the beds, producing different types of flexure in accordance with varying circumstances. Furthermore, the microscopic study of folded rocks shows that they have actually been compressed and mashed and the minutest plications are visible only under the microscope.

Assuming, then, that the folding force was one of compression and acted horizontally, we have next to consider the circumstances which modify the result, producing now one form of flexure or fracture, now another. Such modifying circumstances are the depth to which a given stratum is buried, its thickness and rigidity, the character of the beds which are above and below it, and the intensity and rapidity with which the flexing force is applied. When in a mountain region one sees the manner in which vast masses of rigid strata are folded and crumpled like so many sheets of paper, one perceives the enormous power which is involved in these operations and the gradual, steady way in which that power must have been exerted. When strata are buried under a sufficient depth of overlying rock to crush them, they become virtually plastic and yield to the compressing force by flowing without fracture. At such relatively great depths cavities cannot exist, and if the compressed rock should be broken by the compression, the particles are again welded together into a firm mass. We may accordingly distinguish a *zone of flowage*, in which the rocks all yield plastically, a more superficial *zone of fracture*, in which all but the softest rocks break on compression, and between the two a *zone of fracture and flowage*, in which some rocks break and others flow, according to their rigidity. The depth of the zone of flowage is estimated at 20,000 to 30,000 feet below the surface.

Strata which have not been buried to a sufficient depth to make them plastic, will yield to compression by breaking, though whether a given bed is faulted or flexed, will often depend upon whether the folding force is applied slowly or with comparative rapidity. A force long acting in a slow and steady fashion will produce folds, when the same force applied more suddenly would shatter the beds. Near the surface, under light loads, rigid rocks will always break rather than bend, when compressed. Different stratified rocks differ much in their rigidity, and hence a load which is sufficient to cause one bed to bend and flow, when laterally compressed, will leave another unaffected, or cause it to break, if the compressing force overcomes its strength. In Bald Mountain, New York, the stiff limestones are left unchanged by a pressure which has crumpled and contorted the soft shales.

Another factor of much importance in determining the character and position of folds is the mode in which the strata were originally laid down. As we have already learned, the sheets of sediment which cover the sea-bottom are, on a large scale, nearly level, but they often show slight departures from such horizontality along certain lines. These *initial dips* often determine the place of flexures, because they divert the thrust from its horizontal direction.

The effect exercised by initial dips is shown in Fig. 112, taken from the models experimented on by Mr. Willis, which, when strongly compressed, imitate with remarkable accuracy the structures which may be observed in folded rocks. Fig. 111 shows that in folding, the beds must slip upon each other, as is proved by the lines perpendicular to the bedding planes, which were continuous before folding, but in the anticline are broken by the differential motion of the layers, each bed rising farther up the slope than the one beneath it. The same thing must occur in folded

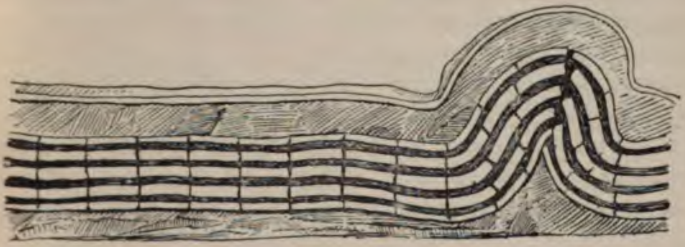


FIG. 111. — Model showing the slip of folded beds upon one another. (Willis.)

rocks, which sometimes show polished bedding planes, due to the slipping of the beds upon one another. The series *A* to *D* (in Fig. 112) represents a model before and in various stages of lateral compression, and exhibits the effect of the slight initial dip at *x* in determining the position of the anticlinal fold, which is developed by compression. The formation of one fold assists in the development of another, for it both changes the direction of the thrust and redistributes the load of overlying strata. The arch of the anticline lifts the load and diminishes the

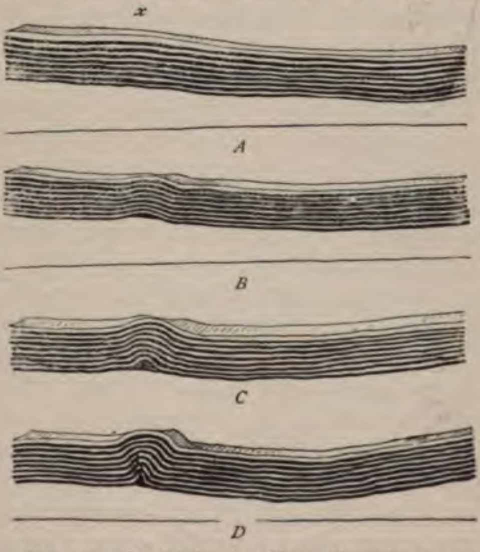


FIG. 112. — Model showing effects of lateral compression. *A*, before folding, with slight initial dip at *x*; *B*, *C*, *D*, in various stages of compression. (Willis.)

weight upon the beds that lie beneath the flexure, but increases the weight upon the lines from which the arch springs.

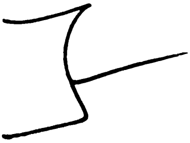
The problem regarding the way in which this great lateral pressure was generated can best be considered in connection with the study of mountain ranges.

There is much independent evidence to show that folding is a gradual process. The force exerted is enormous, but so is also the resistance to be overcome, and a steady or oft-renewed compression, acting upon strata under a great load of overlying masses, will produce regular flexures, where a sudden compression, however intense, could only shatter them.

Thrust or reversed faults are likewise due to lateral compression, by which the rocks have been sheared and broken, and the beds on one side of the plane of fracture have been thrust up over those on the other. A plication or overturned fold may often be traced into a thrust fault, in a way that shows the direction of movement to have been the same in both fold and fracture. Numerous experiments also show that lateral compression will produce just such faults. A reduction of the overlying load, by diminishing the plasticity of the rocks, will occasion shearing and overthrusts, when, under a greater load, the same strata, exposed to an equal force of compression, will simply flex and bend. As we have seen (see Fig. 109), an anticlinal fold whose load has been reduced by erosion, will, on renewed compression, fracture and develop a thrust fault.

Normal or gravity faults are due to tension, because, except in the rare case of those with vertical hade, the faulted strata occupy more space transversely than they did before faulting took place. It is not easy to explain how this tension has been generated. In part, it seems to be due to a sinking of the downthrow side, through the action of gravity, and, in part, to the application of a compressing force acting at right angles to that which produced the folds, thus raising the upthrow side into a very broad and gentle arch, which is parallel to the plane of faulting. Faults of this class are intimately connected with monoclinal folds, into which they sometimes pass, as in the plateau region of Arizona and Utah.

Faults must be comparatively superficial phenomena, because under sufficient load any rock, however rigid, will behave like a plastic body, and will adjust itself to stress by flowage. If this be true, faults must diminish downward, passing probably into flexures below. Faults may also diminish and die away upward, when the fractured beds are much more brittle than those which overlie them.



CHAPTER XIV

CLEAVAGE, JOINTS, MINERAL VEINS, UNCONFORMITY

Cleavage, Fissility, and Schistosity. — *Cleavage* is "a capacity present in some rocks to break in certain directions more easily than in others," while *fissility* is a "structure in some rocks, by virtue of which they are already separated into parallel laminæ in a state of nature. The term *fissility* thus complements cleavage, and the two are included under cleavage as ordinarily defined" (Van Hise). *Schistosity*, or *foliation*, is either cleavage or fissility, or both,

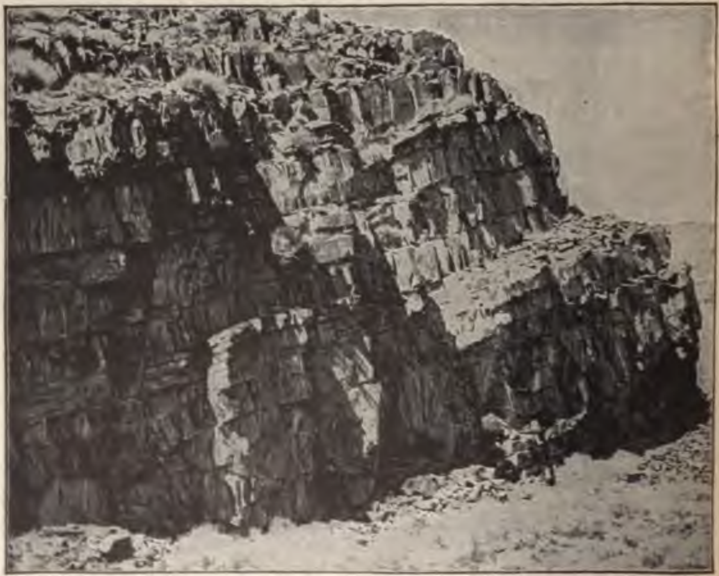


FIG. 113. — Fissile quartzite, California. (U. S. G. S.)

causing the rock to part into plates with a rough or undulating surface, due to the presence of parallel flakes of some mineral.

Many unmodified igneous rocks have a marked cleavage, which is occasioned by the arrangement of the mineral grains with their long axes parallel, or by a parallelism in the cleavage planes of these minerals, or by both factors combined. In cleaved sedimentary rocks the cleavage planes may coincide with the planes of stratification. Much more commonly, however, they intersect the latter at all possible angles, keeping a constant direction for long distances (parallel to the axes of the folds in which they occur), while the bedding planes change with the dip from point to point. Ordinary roofing slate is one of the best possible examples of a cleaved rock, and the structure is often called *slaty cleavage*, to distinguish it from mineral cleavage (see p. 13).

Cause of Cleavage and Fissility. — It is very generally agreed among geologists that slaty cleavage is a result of compression; for, disregarding certain igneous masses, it occurs only in rocks which show other evidences of having been subjected to compression. On the other hand, the mechanics of the problem are somewhat obscure and have given rise to differences of opinion. The most probable view seems to be that the cleavage planes are developed at right angles to the compressing force, and are due to the arrangement of the constituent mineral particles of the rock with their longest diameters, their cleavage planes, or both, in parallel directions. Further, that "this arrangement is caused, first and most important, by parallel development of new minerals; second, by the flattening and parallel rotation of old and new mineral particles; and third, and of least importance, by the rotation

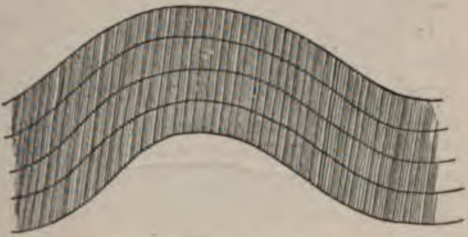


FIG. 114.— Diagram showing relation of cleavage and stratification planes.

into approximately parallel positions of random original particles" (Van Hise). Cleavage is developed by a compressive force at depths where the rocks are under sufficient weight of overlying masses to be plastic, and therefore in the zone of flowage.

Fissility is likewise due to compression, but in this case, the rocks yield along the *shearing planes*, which are inclined and not normal to the direction of pressure. Fissility arises in the zone of fracture where the rocks are not loaded heavily enough to be plastic; but as the depth of this zone varies for rocks of different degrees of rigidity, cleavage may be produced in a softer stratum and fissility in a harder one at the same depth.

Joints. — With the exception of loose incoherent masses, like sand and clay, all rocks, however they may have been formed, are divided into blocks of greater or less size by systems of cracks, known as joints. These may be well observed in any stone-quarry, because the art of quarrying consists in utilizing these natural divisions of the rock. Were it not for them, quarrying would be much more difficult and costly than it is.

In the igneous rocks all the division planes which separate the mass into blocks are true joints, and they vary much in the way in which they intersect one another, and in the consequent shape of the blocks. The fine-grained basaltic rocks display a very general tendency to *columnar jointing*, forming more or less regular prismatic columns, which are more frequently hexagonal than of other shapes. In our study of modern volcanoes (p. 48) we learned that certain modern lavas display these same characteristic hexagonal columns and the ancient basalts of very many regions have them. In certain cases, as in the famous Giant's Causeway, of Ireland, the columns are divided transversely by concave joints, giving a curious "ball and socket" structure, which almost seems artificial. While regular hexagonal columns are much more frequent in the fine-grained basalts, they are not confined to that family. The acid glass of Obsidian Cliff, in the Yellowstone Park, is jointed in the same fashion, though somewhat less regularly (Fig. 15). Mato Tepee of South Dakota is a mass of phonolite, jointed into magnificent columns (see Fig. 127), and other examples might be mentioned. In many of the granites and other coarse-grained igneous rocks, the joints are so arranged as to divide the mass into cubical blocks, or into long, rectangular prisms. In others, again, the blocks are of exceedingly irregular form and size.

In sedimentary rocks the joints are ordinarily in only two planes, the third being given by the bedding planes. In homogeneous, heavily bedded sediments, such as limestones and massive sandstones, the joints are apt to form cubical or rectangular-prismatic blocks, making a weathered cliff look like a gigantic wall of regular masonry. Other sedimentary rocks are, as a rule, more irregularly jointed.

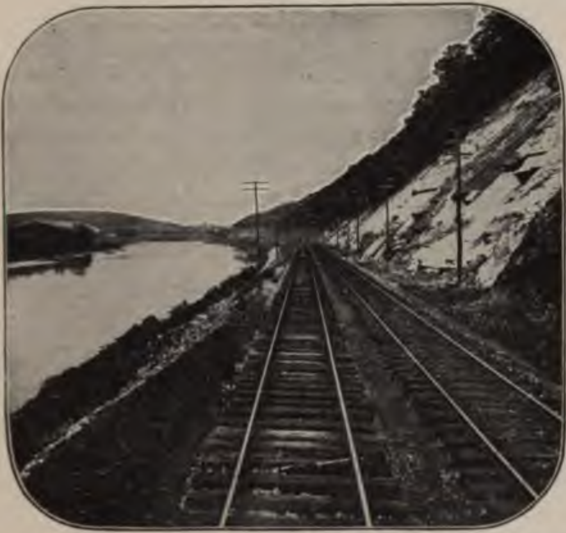


FIG. 115. — Slip Rock, Juniata River, Pennsylvania. Steeply inclined strata, showing joints. (Photograph by Rau.)

Joints are of very different orders of importance: some, the *master joints*, traverse many strata and remain constant for long distances and considerable depths, while each layer usually has minor joints which are confined to that bed. One set of joints, the *strike joints,* run more or less parallel to the strike of the beds, while the second set, the *dip joints*, follow the dip; the former are usually the longer and more conspicuous.

Cause of Joints. — With regard to the manner of their production, joints may be classified into two series: (1) those which are due to tension, the rock usually parting in planes normal to the directions of tension; (2) those which are due to compression, the cracks forming in the shearing planes.

(1) *Tension Joints.* — In igneous rocks joints are caused by the cooling and consequent contraction of the highly heated mass. This shrinkage sets up tensile stresses in the mass to which the rock yields by cracking and parting, the shape of the blocks being largely controlled by the coarseness or fineness of the mass. In some cases the jointing of sedimentary rocks may perhaps be caused by a shrinkage of the mass on drying, but this cannot be an important method of producing systems of joints.

The convex sides of anticlinal and synclinal folds are stretched, and (provided they are not too deeply buried) the stretching may result in a system of cracks radial to the curves which follow the strike of the beds. Folds are not horizontal, but pitch in the direction of their axes. This complex folding may produce two sets of tensile stresses perpendicular to each other, and thus cause two series of joints, one following the strike and the other the dip of the beds. Complex folding must produce a twisting and warping of the strata, and it has been experimentally shown that a brittle substance when twisted cracks in two sets of fractures which intersect nearly at right angles. How slight is the twisting and warping needful to produce joints is shown by the fact that strata which are perfectly horizontal, so far as can be detected, are jointed, as are also certain modern coral limestones.

Tension joints produce either rough, or smooth and sharply cut surfaces, which is determined by the character of the rock. In sandstones which are weakly cemented the cracks pass between the grains, while in hard and firm rocks the fractures are clean.

(2) *Compression Joints* are caused when the rocks yield along the shearing planes. In simply folded strata are produced two sets of strike joints which are inclined toward each other, but whether dip joints will be made by complex folding is not certain. In certain conglomerates the joint planes pass through the hard quartz pebbles and leave a smooth, even, shining face. Tension would pull such a pebble out of its socket and only by shearing could it be cleanly cut. Compression joints are merely a special case of fissility. If the division planes be many and close together, they constitute fissility; if more widely spaced, jointing.

The whole subject of joints in sedimentary rocks is a difficult one and the explanations given of them are not altogether satisfactory, for several other agencies may be involved in their production. It is, however, highly probable that the master joints which roughly follow the strike and dip of the strata, have been caused by the forces which produce folding.

Joints cannot occur in the zone of flowage, and are best developed in the zone of fracture, being of less importance in the transition belt between the two.

Folds and faults, cleavage, fissility, and joints may all be regarded as the varying products of the same set of forces, lateral compression and gravity. Just what type of structure is to result depends upon the circumstances under which the forces are applied, the nature of the rocks affected, the depths to which they are buried, etc. Joints and fissility are minute, incipient faults, and whether a rock is flexed or faulted is determined by its rigidity, the load which it carries, and the gradual or sudden application of the lateral compression.

MINERAL VEINS

The gaping faults and fissures which traverse hard rocks generally remain more or less open for a time, and are frequently filled up by a subsequent deposition of material, quite different from the rock which forms the walls of the fissure or fault and which is called the "country rock." Fissures thus filled by crystallized deposits are called *mineral veins*, which may be either simple or banded. In the former case the vein is filled with a single mineral, while in the latter mineral substances are arranged in bands, which are, in general, parallel to the walls of the fissure. These bands were evidently deposited on the walls of the fissure, for the more perfect ends of the crystals project inward toward the middle line of the vein, and the bands are arranged in corresponding pairs, from the walls inwards. In many instances an apparent departure from this symmetrical arrangement is produced by a reopening of the fissure, so that the older vein forms one of the walls of the new one. Frequently the minerals are associated with an eruption of igneous rock, and the minerals are deposited along the plane of contact between the igneous mass and the country rock.

Often mineral veins contain in greater or less richness the ores of various metals, and then they are called *metalliferous veins*. From such are obtained the greater part of the world's supply of gold, silver, copper, tin, etc. The minerals which form the larger bulk of the vein are called *vein stuff*, or *gangue*, and the ores are either gathered in threads, pockets, or nuggets, or disseminated in fine grains throughout the mass of the vein stuff. The principal minerals which make up the latter are quartz, calcite, barite (heavy spar, $BaSO_4$), and fluor-spar, while the metals are sometimes *native* (*i.e.* in the free, uncompounded state), as are gold and platinum nearly always, and copper frequently, but they much more commonly occur as sulphides, chlorides, oxides, carbonates, or other combination.

The outcrop of a mineral vein at the surface of the ground is much altered by weathering and the true character of the vein may appear only after it has been worked. The chemical changes produced by weathering vary, of course, with the nature of the materials acted on, and a single example must suffice here. In the deeper, unaltered portions of many gold-bearing veins the gold is contained in crystals of iron pyrites. For a varying depth below the surface, the gold is native and is scattered in minute threads and grains through a mass of broken quartz, stained rusty red or brown by iron, while the pyrite has disappeared. The change has been brought about in the following way. Pyrite, on exposure to air and moisture, slowly absorbs oxygen and is converted into the sulphate of iron ($FeSo_4$). The latter is an unstable compound, and continued exposure to air and water converts it into limonite, or ferric hydrate, with liberation of sulphuric acid; the gold is thus left free and the limonite stains the broken quartz rusty brown or red.

As mineral veins so frequently occupy faults, they generally are inclined at high angles, and like faults may be intersected by other veins. If the vein thus cut have any hade, or inclination from the vertical, it will itself be dislocated and slipped, just like an ordinary stratum. In this way we may determine which of two cross veins is the older, for it will be faulted, while the newer one will continue uninterruptedly across the line of intersection.

When we attempt to determine the manner in which mineral veins, and especially the metalliferous varieties, have been formed, we find many facts that are extremely puzzling, and no explanation has been devised that will cover all cases. The great economic importance of metalliferous veins has caused them to be carefully studied in many different parts of the world, but experience gained in one region is apt to be contradicted, in one or more particulars, by that gathered in other regions. In a general way, we may be confident that the minerals were deposited from hot alkaline solutions, brought up from the depths of the fissure, just as we have found to be the case in certain hot springs now active (see p. 130). The vein stuffs show, both by their arrangement in the fissure and by their microscopic characters, that they have been deposited from solution, and such minerals as quartz are dissolved in quantity only by hot alkaline waters. Both from observation and experiment we learn that the alkaline sulphides are the natural solvents of the heavy metallic sulphides, the form in which so many of the ores occur. The materials deposited appear to be derived from various depths of the fissure, and it has been noticed in many instances that the contents of the vein change, as the country rock changes.

Lead deposits occur in a different fashion from the metals mentioned above. In the Mississippi valley, from Wisconsin to Arkansas, are found great quantities of *galena*, the sulphide of lead (PbS), deposited in cavities of limestone; the cavities follow the lines of joint and are largest along the master joints. Associated with the lead frequently occur ores of zinc, pyrite, marcasite, and other minerals. How these remarkable accumulations were formed is altogether doubtful.

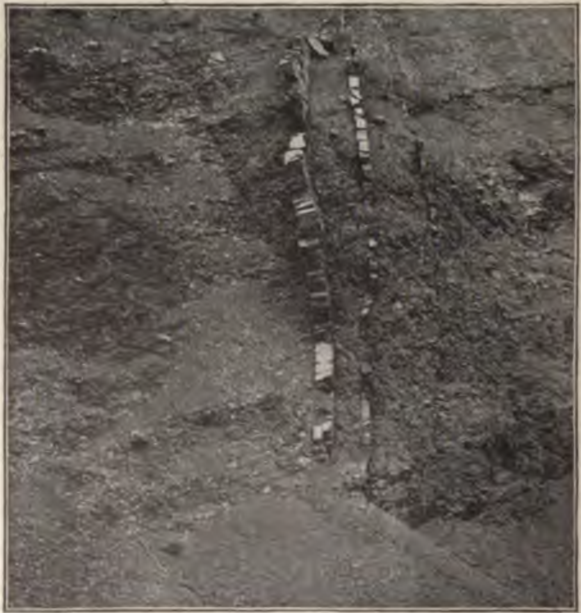


FIG. 116. — Dikes of sandstone in shales. Northern California. (U. S. G. S.)

Sediment-filled Veins. — Vertical fissures are sometimes filled up by sediment washed in from above, but more remarkable are the instances where the fissure evidently did not communicate with the surface and yet was filled with sediment different from the walls. In Fig. 116 is seen an example from northern California: the fissures which traverse the shale have been filled with sand, which, consolidating, has resisted weathering better than the shale and so stands out in relief. These are called *sandstone dikes*, though they are not true dikes, which are of igneous rock. The sand, in this and similar cases, has been forced in by pressure from below while still loose.

UNCONFORMITY

We have hitherto considered the stratified rocks as made up of beds which follow upon one another in orderly sequence, and are all affected alike by the elevation or depression, folding or dislocation, to which they may have been subjected. Strata which have thus been laid down in uninterrupted succession, with sensibly parallel bedding planes, and which have been similarly affected by movements, are said to be *conformable*, and the structure is called *conformity*. In many places, however, the strata exposed in a section are very obviously divisible into two groups, each made up of a series of conformable beds, but the upper group, as a whole, is not conformable with the lower, but rests upon its upturned edges, or its eroded surface. The two groups are said to be *unconformable* and the structure is named *unconformity*. The definition of unconformity here given includes certain not uncommon structures, which must be distinguished as having quite a different significance.

Unconformity is of two kinds. (1) There is a distinct difference in the dip of the two sets of strata, the upper beds lying across the upturned and truncated edges of the lower. This is the more usual kind and is shown in Figs. 117 and 133. The structure implies that the lower series of beds was first laid down under water, and that they were then upturned, tilted or folded to form a land surface. Erosion next truncated the folds, planing the edges of the disturbed beds down to a more or less level surface. The land surface was again depressed beneath the water, and the second set of strata was deposited upon it. Finally, a renewed elevation, accompanied perhaps with folding or faulting, has brought both series of strata above the sea-level.

While the older beds formed a land surface, they were eroded and no deposition took place upon them. Consequently, between the two sets of strata is a gap, unrecorded by sedimentation (at that point), the length of which represents the time that the older beds were above water. The processes involved in an unconformity are of slow operation, so that the gap usually implies a very long lapse of time. In many cases whole geological ages, of incalculable duration, have intervened between the deposition of the two groups of strata.

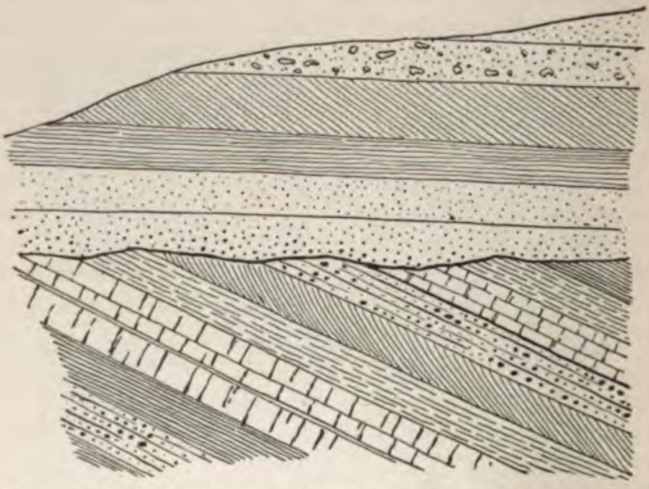


FIG. 117. — Unconformity. Diagrammatic section through the strata seen in Fig. 133, p. 317.

(2) In the second kind of unconformity the two groups of strata have the same dip, the upper series resting upon the eroded surfaces of the lower. The processes involved in this kind of unconformity are nearly the same as in the first, so far, at least, as the alternation of land surface and sea-bottom, elevation and depression, are concerned. In this case, however, the first upheaval was not accompanied by any folding or fracturing of the beds. An unconformity of the second class is sometimes exceedingly difficult to detect and then is called a *deceptive conformity*. Such a

case arises when the surface of the ground is made by cutting down strata to the upper surface of a hard bed, which is then depressed beneath the water, as a flat pavement, upon which new material of a similar kind is laid down with hardly a perceptible break. In the Rocky Mountain region remarkable instances of this deceptive conformity occur, where, in the middle of a mass of limestone apparently formed without any interruption, there is, in reality, an enormous time-gap. Long and careful search has made clear the nature of the contact and exposed the deception.

The lowest member of the upper series of strata in an unconformity is very frequently a conglomerate or coarse sandstone, and represents the beach formation of the sea advancing over the old land. These are called *basal conglomerates*. Such coarse beds are, however, not always present, and they may be only locally developed along a particular line.

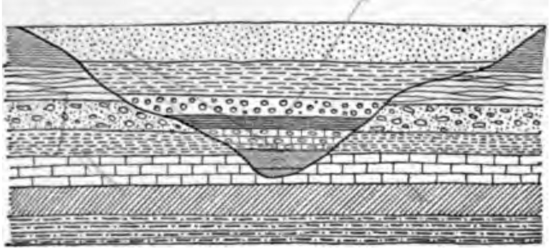


FIG. 118. — Unconformity without change of dip, and overlap.

Unconformities may be confined to relatively restricted regions, or they may extend over whole continents; they are very useful means of dividing the strata into natural chronological groups.

Overlap. — When a series of strata is deposited in a basin with sloping sides, or on one sloping side, each bed will extend farther than the one upon which it lies, and thus in a thick mass of strata, if the shelving bottom be gently inclined, the upper beds will extend far beyond the lower ones, or *overlap* them. (See Fig. 118.) Overlap also occurs where the sea is advancing or transgressing slowly across a subsiding land surface, the rate of depression not much exceeding the rate of deposition. Here also each stratum extends farther across the old land surface than the one beneath it, and conceals the edges of the latter. The relation of overlap is between the successive layers of a *conformable* series.

Overlap may be a structure of much economic importance, if one of the lower strata, say a coal-bed, is mined. It is not safe to assume that wherever the upper beds of such a series are found, the lower will be found directly beneath them, an assumption which may result in costly failure.

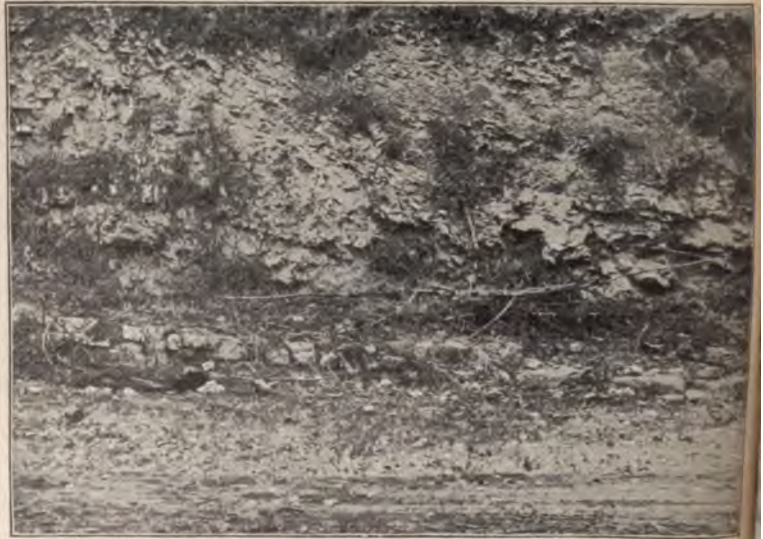


FIG. 119. — Contemporaneous erosion in limestone, Iowa. (Photograph by the Iowa Geological Survey.)

Contemporaneous Erosion. — It was stated above that the definition of unconformity, as given, would include certain structures, which, nevertheless, must be distinguished from it: one of these is contemporaneous erosion. This structure is produced when a current of water excavates channels for itself in the still soft and submerged mass of sediment. After the current has ceased to flow, renewed deposition fills up the hollow with the same or a different kind of material as was thrown down before. This structure requires only a short pause in deposition, not a long, unrecorded break, and does not necessarily involve movements of elevation and depression. Furthermore, contemporaneous erosion is a local phenomenon, and though in a limited section it may not always be easy to distinguish it from an unconformity, the difference becomes apparent when a wider area is examined. If the structure be one of contemporaneous erosion, the two series of strata will be conformable except along the line of the channel or channels. In Fig. 119 is an example of this structure and shows where a channel in an ancient sea-bottom of calcareous material was filled up by a later deposition of similar substance.

The clay "horses" (as miners call them), which frequently interrupt coal beds, are the channels of streams which meandered through the ancient peat bog, and which were filled up with sediment when the swamp became submerged. The "horses" are usually of the same rock as that which forms the cap or roof of the coal seam.

Horizontal and Oblique Bedding. — Another kind of deceptive resemblance to unconformity is occasionally caused by the alternation of horizontal and oblique bedding, a horizontal bed resting upon a series of inclined layers. A conspicuous example of this is given by the Le Clair limestone of Iowa, which was at one time altogether misunderstood, but the deception is seldom one that a little care will not expose. (See also Fig. 77.)

CHAPTER XV

UNSTRATIFIED OR MASSIVE ROCKS

THE unstratified or massive rocks have risen in a molten state from below toward the surface, though by no means always reaching it, and have forced their way through or between the stratified rocks. One of the most important points to determine with regard to a massive rock is its relation to the strata in which it occurs; for the earth's chronology is given by the stratified rocks. Considered only with reference to itself, an igneous mass gives no trustworthy evidence as to the time when it was formed. The term *eruptive* is frequently employed in the same sense as unstratified, because of the belief that most igneous masses have been connected with volcanoes; but as such a belief may not be well founded, it is better to use a non-committal term.

We shall first take up the volcanic rocks, because modern volcanoes give us the key by which we may readily interpret them.

I. ANCIENT VOLCANOES AND THEIR ROCKS

Volcanic Necks. — Volcanoes, like all other mountains, are subject to the destructive effects of the atmosphere, rivers, and the sea. In an active volcano the upbuilding by lava flows and fragmental ejections more than compensates for the loss by weathering, and the cone continues to grow in height and diameter. When the volcano has become extinct, the destructive agencies work unopposed. We find extinct volcanoes in all stages of degradation, from those which look as though their activity might be renewed at any moment, to those which require the careful examination of a skilled geologist to recognize them as what they are.

In the Pacific States may be found admirable examples of volcanic cones in various stages of erosion. In northern Arizona the picturesque San Francisco mountains, themselves volcanic, are surrounded by numerous small and very perfect cones, hardly affected by weathering. In northern California stands the noble peak of Mt. Shasta (Fig. 18), which was active till a late geological date and still shows traces of activity in its hot vapours, but has begun to suffer notably from weathering. Still farther north, in the State of Washington, is Mt. Rainier, another volcanic cone, which has been longer exposed to the destructive agencies and has been worn into an exceedingly rugged peak.

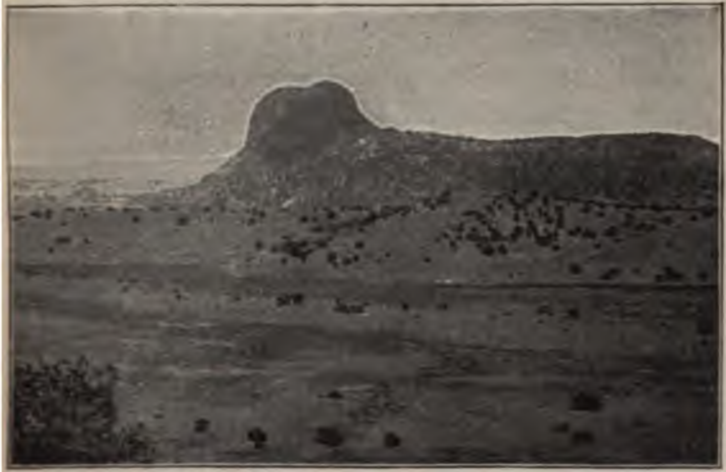


FIG. 120. — Volcanic neck, New Mexico. (U. S. G. S.)

These mountains, however, merely exemplify the earliest stages of degradation ; as time goes on, the loftiest cones will be worn away, all the more rapidly, if they be composed principally of fragmental materials. At last only the worn-down and hardly recognizable stump of the volcano remains, which is known as a volcanic neck. The neck consists of the funnel or vent filled up with the hardened lava of the last eruption, or, less commonly, with a mass of volcanic blocks. Associated with this plug of lava may be preserved the lowest lava flows or tuffs of which the cone was originally built up. If the land upon which the volcanic neck stands be covered by the sea or other body of water, the remnant of the cone will be buried beneath sediments, and a volcanic island may be similarly cut down and covered with sediments. Subsequent upheaval and denudation may at a long subsequent time once more expose the buried cone to view. Several examples of this have been found in Great Britain.

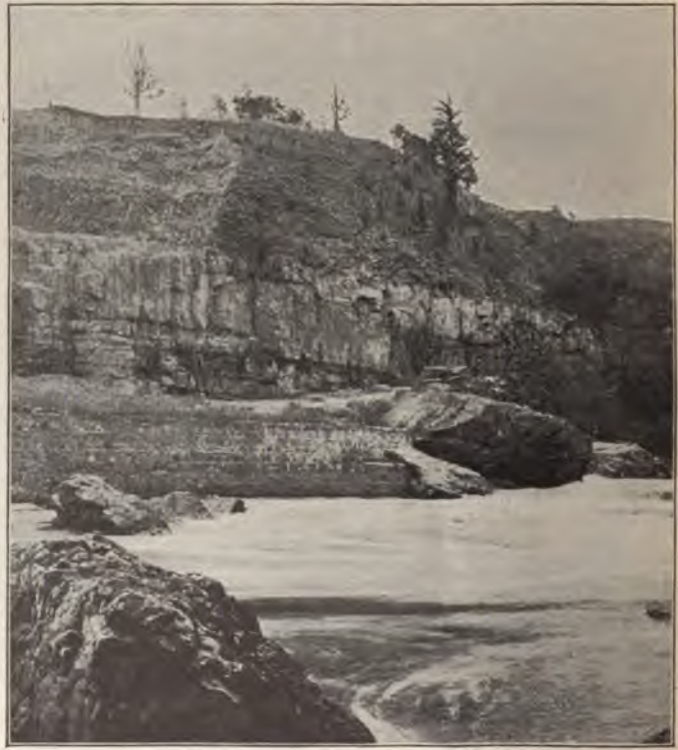


FIG. 121.—Jointed lava flow. Passaic River, New Jersey. (U. S. G. S.)

Lava Flows and Sheets which were poured out on the surface of the ground may be recognized by the aid of several criteria. In flows of only moderate antiquity, which have suffered little denudation, the nature of the mass may be determined at a glance, and traced to the vent whence it issued. Successive sheets, piled one over the other in a rude bedding, are also evidence that the rocks are surface lavas. (See Fig. 21, p. 57.) Surface sheets may be overlaid by sediments, deposited upon a submarine flow, or after depression of the land. Such a flow is then called a *contemporaneous* or *interbedded sheet*, and evidently its geological age follows the rule for strata; it is newer than the bed upon which it lies and older than the one which rests upon it.

Fragmental Products (Pyroclastic) are positive proof of volcanic action, for they cannot be formed underground. Coarse masses of agglomerate, blocks, and bombs show that the vent from which they issued was not far away, while beds of fine ashes and tuffs may be made at great distances from their source. All these varieties may be enclosed in true sediments, and may, in part, escape destruction long after the volcano which ejected them has been cut away. The fragmental products are always contemporaneous, and when interstratified with sediments are newer than the underlying, older than the overlying stratum.

II. ROCKS SOLIDIFIED BELOW THE SURFACE (PLUTONIC)

We now come to a series of rocks which no one has ever observed in the course of formation, because they were solidified at greater or less depths beneath the ground. When such masses are exposed to view, it is not because they have been brought to the surface, but because the surface has been eroded down to them. Though these unstratified masses cannot be observed in the process of formation, as may the lavas and pyroclastic rocks, yet the nature of the rocks themselves, and their relations to the volcanic and stratified rocks, enable us to explain them satisfactorily. In whatever shape they occur, these masses are *intrusive*, and have forced their way upward, filling fissures and cavities, or have thrust themselves between strata, following the path of least resistance. Intrusions are younger, it may be vastly so, than the strata which they penetrate and lie over or beneath; their geological date may be determined by a process of elimination, finding the newest strata which they have traversed and the oldest which they have not reached.

Different names are given to these subterranean masses, in accordance with their shape, size, and relation to the strata with which they are associated.

Dikes. — A dike is a vertical or steeply inclined wall of igneous rock which was forced up into a fissure when molten and there consolidated. Dikes of a certain kind may actually be seen in the making, as when the lava column of a volcano bursts its way through fissures in the cone. The ordinary dike is formed in fissures which traverse stratified rocks, or, sometimes, cuts through older and already consolidated igneous rocks. In thickness dikes vary from a foot to a hundred feet or more, and pursue nearly straight courses, it may be for many miles. The rock of a dike has usually a compact texture, having cooled more slowly than the volcanic masses, though the edges, chilled by contact with the walls of the fissure, may be glassy. If the rock displays columnar jointing, the prisms are horizontal, normal to the cooling surfaces.

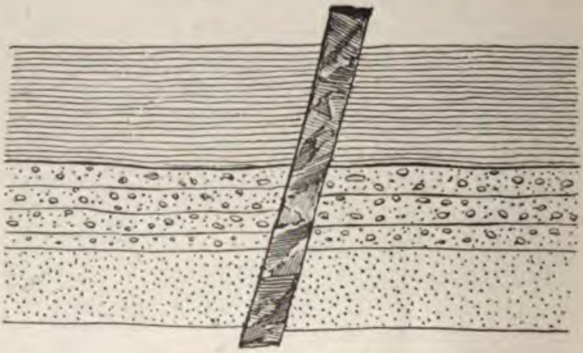


FIG. 122. — Diagram of dike.

The commonest rocks in dikes are basalt, quartz porphyry, andesite, and diabase.

When denudation has so far cut away the surface of the ground as to expose the dike, the form which the latter takes will depend upon the relative destructibility of the igneous rock and the enclosing strata. If the latter wear away more rapidly, the dike will be left standing above the surface like a wall (Fig. 122); but if the igneous mass be disintegrated more rapidly than the strata, a trench will mark the line of the dike.

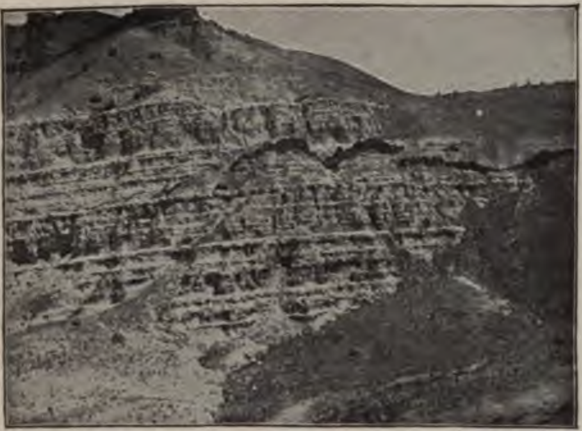


FIG. 123. — Dike of basalt cutting strata: bad lands of eastern Oregon.

Dikes are common and conspicuous objects in the Connecticut valley and in the sandstone belt which runs, with interruptions, from the Hudson River to North Carolina.

Veins are smaller and more irregular, frequently branching fissures which have been filled with an igneous magma; they may be only a few inches in thickness, and may often be traced to the mass which gave them off. The nature of the rock in a vein may be much modified by material derived from the walls. This vein rock is often so coarsely crystalline, that it has been suggested that it could not have solidified from fusion, but was deposited from a solution in superheated waters.

Intrusive Sheets or Sills. — These are horizontal or moderately inclined masses of igneous rock, which have small thickness as compared with their lateral extent. Sheets conform to the bedding planes of the strata, often running long distances between the same two beds; but if they can be traced far enough, they may generally be found cutting across the strata at one point or another. In thickness they vary from a few feet to several hundreds of feet. The Palisades of the Hudson are formed by a sheet of unusual thickness; its outcrop is 70 miles long from

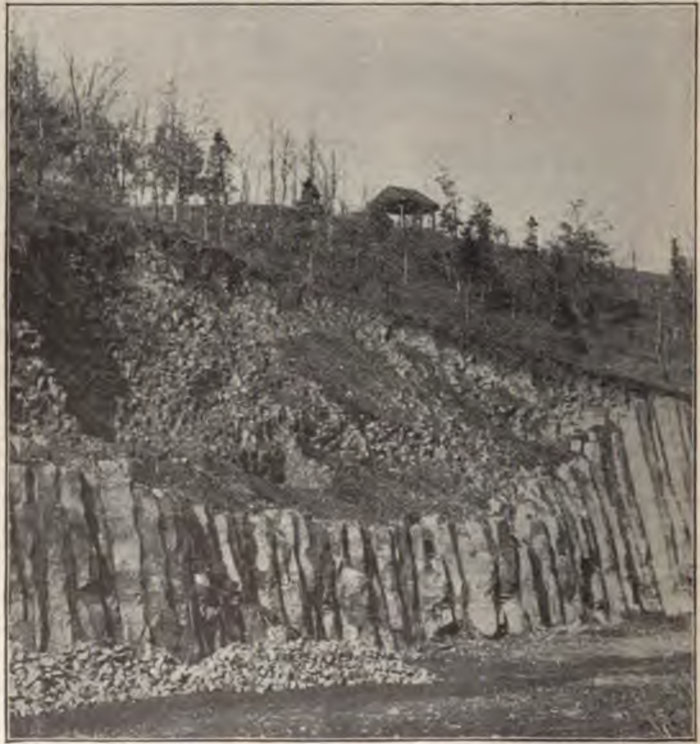


FIG. 124. — Sheet of jointed diabase. Orange, N.J. (U. S. G. S.)

north to south, and its thickness varies from 300 to 850 feet; the dike which supplied this immense mass is exposed in a few places along its western edge.

Intrusive sheets are most commonly formed in horizontal strata, which offer less resistance to horizontal expansion than do the folded beds; they are also very generally of the most fusible family, the basaltic, because such magmas retain their fluidity and flow for longer distances than do the highly siliceous rocks. It is probable that intrusive sheets can be formed at only moderate depths, because the overlying strata must be lifted to an amount equal to the thickness of the sheet. At great depths the weight to be lifted is so enormous, that the easiest path of escape must be by breaking through and across the strata. If the beds are subjected to compression after the intrusion of the igneous masses, the latter will be flexed or faulted like the stratified rocks.

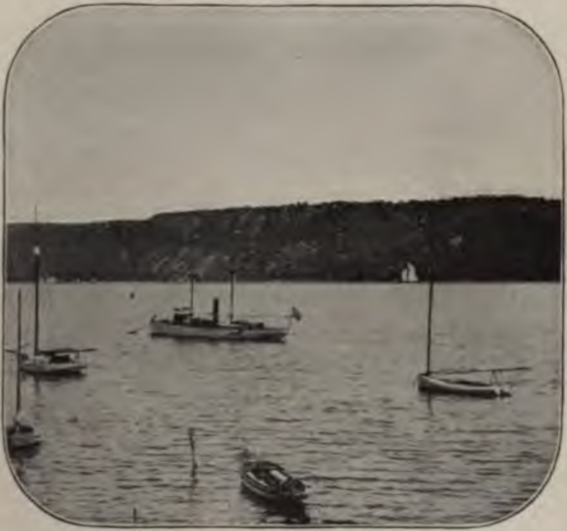


FIG. 125.—Palisades of the Hudson, New Jersey. (Photograph by Rau.)

In a limited exposure it is often difficult to distinguish at once between an intrusive and a contemporaneous sheet, but there are certain characteristic marks which enable the observer to decide. The presence of scoriæ shows that the sheet is contemporaneous. If, on the other hand, the *overlying* stratum be baked and altered by the heat, or if the sheet cuts across the bedding planes at any point, or if it can be traced to a dike which rises above it, or if it gives off tongues or veins, or if pieces of the overlying stratum be torn off and included in the sheet, it must be intrusive. The nature of the contact between the sheet and the stratum above it is also significant; if the former be contemporaneous, the cracks and fissures of its upper surface will be filled with the sedimentary material. Finally, the texture of the igneous mass gives valuable evidence; in the intrusive sheet the texture is compact

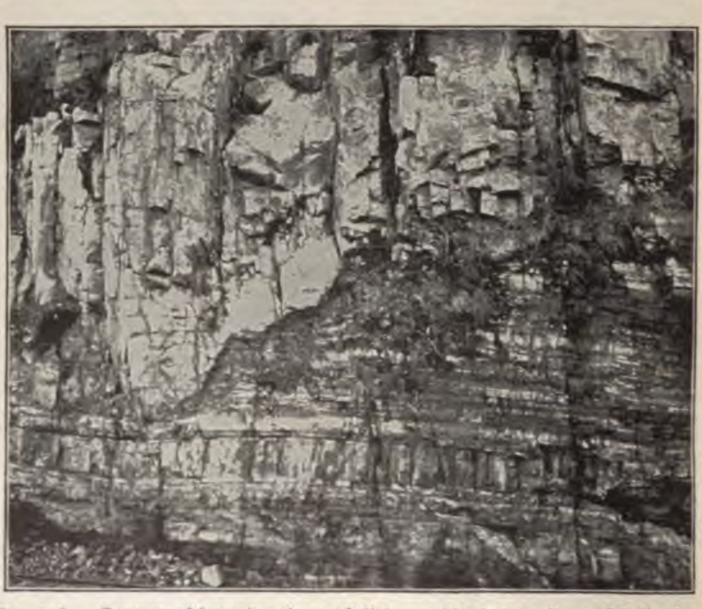


FIG. 126. — Contact of intrusive sheet of diabase with shales. Base of Palisades, Wiehawken, N.J. (U. S. G. S.)

(without glassy ground mass) or even quite coarsely crystalline, while the contemporaneous sheet will display the glassy or porphyritic texture of surface flows.

Laccoliths. — A laccolith (or laccolite) is a large, lenticular mass of igneous rock, filling a chamber which it has made for itself by lifting the overlying strata into a dome-like shape. The rock of which laccoliths are made is nearly always of the highly siliceous and less fusible kinds, so that it can more easily lift the strata than force its way between them. Intrusive sheets are, it is true, often given off from a laccolith, but these are of quite subordinate importance, while dikes and irregular protrusions extend into the fissures of the surrounding and overlying strata. Subsequent erosion may remove the dome of strata and cut deeply into the igneous mass beneath, leaving rugged mountains, the height of which depends upon the amount of original uplift and the subsequent denudation. Laccoliths in various stages of denudation occur in different parts of the West. Fig. 128 shows Little Sun Dance Hill in South Dakota, a small dome from which the overarching strata have not been removed and the igneous core has nowhere been exposed, yet there can be little doubt of its presence. In the same region is Mato Tepee (also called the

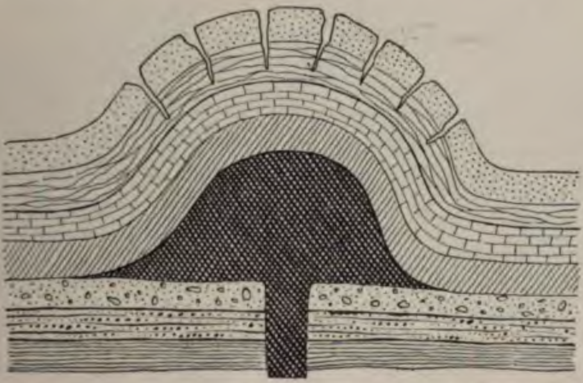


FIG. 127. — Diagram of uneroded laccolith. (Modified from Gilbert.)

Devil's Tower), a magnificent shaft of columnar phonolite, which rises 700 feet above a platform of horizontal strata. This tower is the remnant of a laccolith from which the covering strata, and probably much of the igneous core, have been eroded away. In southern Utah the Henry Mountains are a group of laccoliths from which several thousand feet of overlying strata have been removed and the cores deeply dissected. In the Elk Mountains of Colorado are some enormous laccolithic masses.

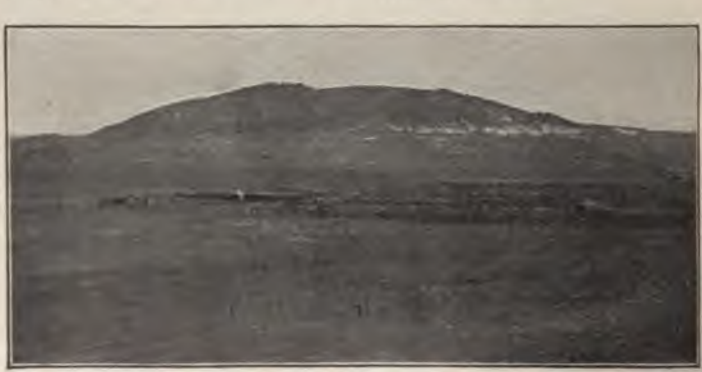


FIG. 128. — Little Sun Dance Hill, South Dakota. (U. S. G. S.)

Bosses are rounded or irregular masses of intrusive rock, which may be only a few feet or several miles in diameter. Their exposure on the surface is due to the removal of overlying strata, and their prominence as hills is caused by their greater resistance to denudation than that of the enclosing stratified rocks. Some bosses are believed to be the subterranean reservoirs which once supplied volcanoes; but this can rarely be proved, because when the boss is exposed by denudation, the volcanic neck has been swept away. However this may be, many bosses probably never communicated with the surface by any vent. Veins, dikes, sheets, and various irregular protrusions are frequently given off from bosses. Bosses are made up of the granitoid, compact or porphyritic members of various rock groups: granite, diorite, basalt, and gabbro are especially common, and the coarseness of the

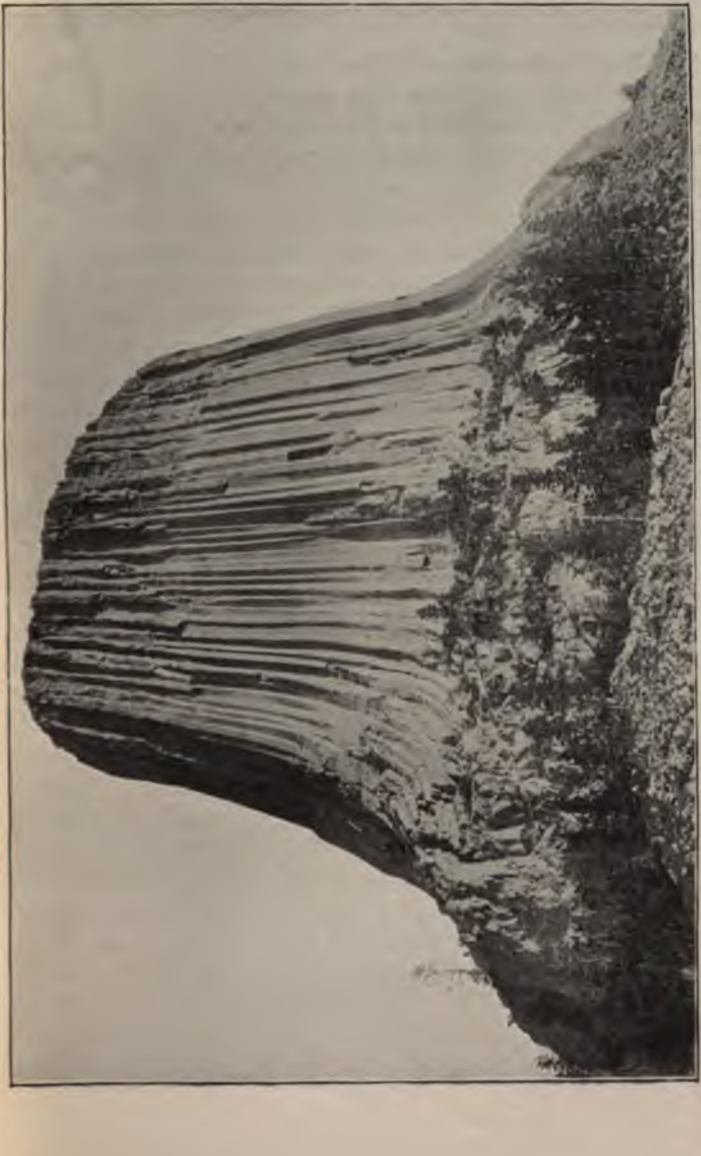


FIG. 129.—Mato Tepee, South Dakota, the core of a laccolith composed of columnar phonolite.

component crystals usually increases from the circumference to the centre of the mass.

Bathyliths are huge masses of igneous rock, which may be scores or hundreds of miles in extent, and are of entirely irregular shape. Like bosses, they are exposed to view only when denudation has cut the surface down to the level at which they were formed. It is difficult to understand how such vast quantities of material could have been forced upward, except by melting their way, at least partly, through the overlying rocks.

From this brief description it will be apparent that the various forms of igneous rock which present themselves to our study are the outcome of the interaction of several factors, such as the ascensive pressure, the resistance to be overcome, and the fluidity or stiffness of the molten magma. Such masses have played a very important rôle in the modification of the earth's surface, both by the displacement of previously existing rocks and by the addition of new and different material.

CHAPTER XVI

METAMORPHISM AND METAMORPHIC ROCKS

By the term *metamorphism* is meant the profound transformation of a rock from its original condition by means other than those of disintegration. The incipient changes of the latter class may very greatly modify a rock and its constituent minerals, but such changes are distinguished from metamorphism under the term *alteration*. Metamorphism usually implies an increase in hardness and in the degree of crystallization, and very frequently also the generation of an entirely new set of minerals, which take on a characteristic arrangement. The degree of metamorphism varies according to circumstances, and from the mere consolidation of loose sediments to the most radical reconstruction of the rock, there is every possible transition. Fossils may be found in those metamorphic rocks of sedimentary origin, which have not been completely changed. The more thorough the reconstruction of the rock, the more obscure do the fossils become, and in advanced stages nearly all trace of them is obliterated.

For many years it was supposed that the metamorphic rocks were one and all transformed sediments, but later investigations have shown that many of them were originally igneous. Indeed, it is often quite impossible to decide whether a given metamorphic rock has been derived from a sedimentary or an igneous original. This is not surprising, for the ultimate chemical (not the mineralogical) composition of a basalt, a volcanic tuff, or a clay shale, may be the same, and the metamorphic processes may produce an identical rock from any one of these three as a starting-point. Much yet remains to be learned regarding the modes, causes, and results of metamorphism and some of the most far-reaching problems of geology are bound up with these questions.

Metamorphism is of two quite distinct kinds: (1) contact or local, and (2) regional metamorphism.

I. CONTACT METAMORPHISM

This is the change effected in surrounding rocks by igneous intrusions, dikes, bosses, etc. The rock invaded and metamorphosed may be either sedimentary, igneous, or already metamorphic, and the effects may be very marked, or surprisingly small; indeed, it is often quite impossible to say why the changes should be so insignificant. Plutonic rocks are more effective in producing these changes, because they are, presumably, hotter and retain their heat longer. Magmas which contain an abundance of the mineralizing vapours (see p. 192) produce much more effect than those with only a small quantity of such vapours. For this reason acid magmas are more effective than basic. Much, too, depends upon the nature of the invaded rock; sediments which contain large percentages of alumina and lime are much more readily and profoundly changed than those which are made up almost entirely of silica. The distance to which the zone of change extends is wider when the intrusive mass cuts across the strata than when it follows the bedding planes, so that a dike or boss is more effective than a sheet.

We may now consider some examples of contact metamorphism, and, for this purpose, shall select only the changes of sedimentary rocks; for those of the other classes require a treatment too minute and refined for an elementary work. We may note, in passing, however, that some of the veins given off from granite bosses, which have invaded other igneous rocks, are probably of a metamorphic nature and due to the penetration of vapours.

In a series of strata which have been invaded by an igneous mass, we find a gradual change from the unmodified rock which lies beyond the reach of the transforming agencies, to that at the actual contact with the igneous mass. Along this line of contact the strata are so thoroughly reconstructed that often only a microscopical examination will distinguish the changed sediment from e igneous rock. A siliceous sandstone or conglomerate de-elops no new minerals in the change, or only in insignificant uantity from the impurities present. The bulk of the material mply crystallizes and forms the white rock, *quartzite*. Clay cks undergo more radical change and are usually divisible into istinct zones; the outermost zone is unchanged; in the inter-ediate one the shale is changed to a dense *slate* spotted with iotite, magnetite, or other dark minerals. The spotted slate asses gradually into *mica schist*, a rock made up of flakes of ica, with some quartz and felspar, arranged in rudely parallel lanes. At the contact the rock is converted into *hornfels*,[1] which a very dense substance, looking like trap, and filled with numer-us silicated minerals, such as hornblende, felspar, and many hers which were not enumerated in the chapter on the rock-rming minerals.

Pure limestone is crystallized by the heat into white marble, t as most limestones contain impurities, they develop, when etamorphosed, a large variety of minerals, such as biotite, gar-et, amphiboles, pyroxenes, etc. Beds of bituminous coal are aked into a natural coke, as in Virginia and North Carolina, or anged to anthracite, as in Colorado, and limonite is converted to magnetite.

In contact metamorphism, the mere molecular rearrangement d chemical recombination of materials already present in the ck are not the only changes which occur. Two other processes, *mentation* and *injection*, frequently produce important results. ementation is the deposition of mineral matters from solution in e interstices between the granules of the rock. Quartz, calcite, on oxides, felspars, mica, augite, and other minerals may be us introduced, and sometimes the quantity of new material ought into the rock is very large. Injection is the penetration a rock by molten substances which may not only fill up all e minute crevices, but even force their way between the con-ituent granules. The distinction between cementation and injection is not a very sharply marked one, because superheated water and molten magmas appear to mix in all proportions. The difference between the two processes seems thus to be largely a question of the quantity of water present.

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[1] Also called *hornstone*, but as this term is used for flint, it is best to retain it in latter sense only.

Contact metamorphism, as its name implies, is a local phenomenon, but a widely ramifying and complex system of igneous intrusions may change large areas of sedimentary rocks.

II. REGIONAL METAMORPHISM

This term applies to the reconstruction of rocks upon a great scale, in areas covering, it may be, thousands of square miles, and evidently other processes in addition to those of contact metamorphism are needed to explain such wide-spread changes. A very general characteristic of such metamorphic rocks is *foliation*, or *schistosity*. This is either cleavage or fissility (see p. 260), or both, which causes the rock to part into plates with rough or undulating surfaces, due to the presence of flakes of some mineral arranged in rudely parallel planes. Schistosity is connected by every transition with cleavage or fissility, and represents an advanced degree of metamorphism, as the latter processes are incipient stages of the same.

The first step in metamorphism consists in a mere hardening of the rock, accompanied with the loss of water and other volatile substances. In the second stage the component minerals are crystallized, but new compounds are sparingly formed. The shearing or crushing to which the mass has been subjected frequently change minerals into *paramorphic* forms, *i.e.* those which have the same chemical composition, but different crystalline form and physical properties. For example, aragonite is thus changed to calcite, and augite to hornblende. This stage is frequently accompanied by cleavage or schistosity. In the more advanced stages the rocks are foliated, and complete chemical reorganization may take place, with the abundant development of new minerals. The compression and consequent shearing and crushing to which the rocks have been subjected are the principal agents of the changes, though igneous intrusions frequently add very materially through the extensive development of contact metamorphism.

The igneous rocks, when subjected to the same processes, give rise to rocks similar to those made from the metamorphism of sediments. The compression, shearing, and crushing may take place while the molten mass is still pasty, or long after the rock has cooled. Certain rocks have been formed from the metamorphism of sediments and the injection of igneous material, and are thus of highly complex origin.

III. The Causes of Metamorphism

This is a subject which bristles with difficulties, and of which our knowledge is yet very incomplete, though, in a general way, the agencies of the transformation are intelligible.

(1) **Heat** is evidently a very important factor of the change. This is made plain by the phenomena of contact metamorphism and by the numerous successful attempts to imitate metamorphism experimentally. On the other hand, it is not believed that high temperatures are always indispensable. Change in which heat is the principal factor is called *thermal metamorphism.*

(2) **Compression** is the principal agency in regional metamorphism, and to it are due the structures of cleavage, fissility, and schistosity, as well as the reconstruction and crystallization of mineral particles. This is *dynamic metamorphism*, but heat is probably a common accessory in this method of change also. To be in the zone of flowage, rocks must be so deeply buried that they are invaded by the earth's internal heat; and unless the movement be excessively slow, flowage must generate frictional heat.

(3) **Moisture** is likewise a potent cause of change. Under pressure, water may be heated to very high temperatures, when it becomes capable of attacking and dissolving or decomposing the most refractory substances, and building them up into new compounds. Many minerals, such as orthoclase and quartz, which

have never been experimentally made by dry heat, may be readily compounded and crystallized with the aid of superheated water. Furthermore, the presence of water diminishes the temperature necessary to affect metamorphic changes; and rocks which require a heat of 2500° F. to melt them in the dry state, will in the presence of water become pasty and viscous at 750° F. In contact metamorphism other mineralizing vapours and gases play an important part.

(4) **Pressure** is a necessity for any extensive metamorphism, whether thermal or dynamic, to produce the necessary plastic flow or shearing of the rocks, and to prevent the escape of the steam and gases. Limestone heated in an open vessel becomes quicklime (CaO), because the CO_2 is driven off at high temperatures. Heated under pressure, the same limestone will crystallize into marble. On a large scale, therefore, metamorphism can be effected only at considerable depths; for it is in the zone of flowage that the most favourable conditions are to be found.

It is believed by certain geologists that metamorphism may proceed so far as to completely melt a sedimentary rock and thus produce a magma which is indistinguishable from a typically igneous one. Some have even maintained that the lavas now ejected from volcanoes are but the final results of metamorphism. These conceptions may possibly approximate the truth, but the progress of investigation is at present leading away from them. No instance is yet known which renders it necessary to assume that a given igneous rock was made from melted sediments, and the cases which have been relied upon to prove the hypothesis have, for the most part, been shown not to require such an explanation. On the other hand, certain metamorphic rocks do form a common meeting-place for the igneous and sedimentary classes, and, as we have seen, it is frequently impossible to decide from which class a given metamorphic rock was originally derived.

Owing to this uncertainty regarding their derivation, the metamorphic rocks of igneous origin are, to some extent, included with those formed from sediments in the schemes of classification.

IV. METAMORPHIC ROCKS

A. NON-FOLIATED ROCKS

These represent the less advanced stages of metamorphism, in which the forces of compression may have produced cleavage or fissility, but not foliation. The more important rocks of this class are of sedimentary origin, and it will be unnecessary for us to consider the igneous rocks which have been changed, though not to the extent of producing foliation.

Quartzite is derived from the metamorphosis of sandstone, and between the two kinds of rock are found such complete transitions, that the separation of them seems almost arbitrary. In a typical quartzite the rock is crystalline, and the quartz deposited around the sand-grains is in crystalline continuity with those grains, though the microscope still reveals the original fragmental nature of the rock. Quartzites also result from the metamorphism of conglomerates, and the pebbles are sometimes much flattened by compression. If the sandstone or conglomerate contained impurities, other minerals beside quartz are generated; if any considerable quantity of clay was present, mica will be produced and, it may be, in such abundance that the rock passes into mica schist (see below).

Quartzites are formed both in contact and regional metamorphism, but the change is principally due to cementation, large amounts of silica (estimated as one-sixth of the original quantity present in the sandstone) being brought in and deposited from solution. Many quartzites do not appear to have been subjected to great compression, though others are cleaved or fissile (Fig. 113).

Greywacke is a hard, crystalline rock, of banded appearance and characteristic grey colour. The sedimentary original is either a mudstone, an arkose, or a mass of fragments of felspar, mica, quartz, and other igneous minerals which have been mechanically abraded, but little or not at all decomposed. The change is due largely to cementation, the sand-grains being enlarged as in quartzites, and silica is deposited in the interstices, binding the whole mass firmly together. The other minerals undergo a great variety of changes, according to the amount of compression and mashing which the rock has undergone. *Greywacke-slate* is fine-grained and parts into plates parallel with the stratification planes.

Slate and Phyllite. — Slate is a fine-grained, dense, and hard rock, which, when metamorphosed by compression, is cleaved. It results from the transformation of clay shales, fine arkose, and sometimes of volcanic tuffs. Crushed fragments of felspar change into interlocking crystals of quartz and felspar, or quartz and mica. The mineral particles, both original and newly developed, have a parallel arrangement of their long axes and cleavage planes, which determines the cleavage of the rock. In colour, slates are usually drab, or dull dark blue, but they may be brick-red, green, or purple. When fine-grained and regularly cleaved, they are extensively quarried for roofing purposes. Great areas of them occur in Vermont, eastern Pennsylvania, Virginia, and Georgia, south of Lake Superior, and on the western flank of the Sierra Nevada.

Phyllite is slate in a more advanced stage of metamorphosis, in which the mica spangles are more abundant, and visible to the naked eye, giving lustrous surfaces to the cleavage planes. Like micaceous quartzite, phyllite may often be traced into mica schist.

Marble is a metamorphic limestone, in which the fragments and particles of organic origin have been converted into crystalline calcite. Magnesian limestones yield crystalline dolomites, which are likewise included under marble. In the process of reconstruction, the fossils and even the bedding planes of the original limestone are usually entirely obliterated. The grain of the rock varies much, from the fine, dense, loaf-sugar-like statuary marble to a very coarse texture of large crystals. Pure limestone gives rise to a white marble, but the presence of organic matter is betrayed by veins of graphite, which may indicate the lines of mashing and flow, along which the rock yielded to the compressing force. Iron and organic matters present in the limestone produce a great variety of coloured and variegated marbles, some of which are of extraordinary beauty. The sand and clay present in many limestones will, on metamorphosis, give rise to a variety of silicated minerals.

Marble is an exceptional case of a completely crystalline rock derived from sediments by dynamic metamorphism, which is not foliated or schistose. This is believed to be due to the capacity of calcite to recrystallize freely after it has been subjected to compression and mashing.

The economic value of the marbles makes them largely sought after; in this country they are extensively developed along the Appalachian region, from Vermont to Georgia, in the Rocky Mountains, and the Sierra Nevada.

The **Ophicalcites** are crystalline magnesian limestones and dolomites, with varying amounts of included serpentine, which gives them a mottled appearance. They are not thoroughly understood, and it appears that they may be formed in various ways. Some ophicalcites are almost certainly marbles, in which inclusions of olivine, pyroxene, or hornblende have been formed and afterwards altered into serpentine (see p. 22). Others would appear to be broken and fissured serpentines, having the crevices filled up with calcite deposited from solution.

Anthracite is usually regarded as a metamorphic form of coal, and, as we have seen in a preceding paragraph of this chapter, it is formed from bituminous coal by contact metamorphism. On a large scale it occurs chiefly in areas of folded and disturbed rocks, though not invariably so. A more intense metamorphism of carbonaceous material gives rise to *graphite* (or black lead), a semi-crystalline form of carbon, which, however, is a mineral rather than a rock.

B. FOLIATED ROCKS

The foliated or schistose rocks are those which are divided into rudely parallel planes, with rough or undulating surfaces, due to the flakes and spangles of some mineral. The planes of foliation may coincide with the original bedding planes or they may intersect the latter at any angle, just as do the planes of cleavage and fissility. The foliated rocks represent the most advanced stage of what we can confidently call metamorphism, and may be derived from either sedimentary or igneous originals; it is not always possible to say which.

Gneiss is a term of wide significance, which includes a number of rocks of different modes of origin and different mineralogical composition. It is "a laminated metamorphic rock that usually corresponds in mineralogy to some one of the plutonic types" (Kemp). The varieties of gneiss are ordinarily named in accordance with the most conspicuous dark silicate present, as *biotite gneiss, hornblende gneiss*, etc.; but this system of nomenclature gives an imperfect notion of the character of the rock. A better method, recently suggested (C. H. Gordon), is to name the varieties in accordance with the igneous rocks to which they correspond in mineralogical composition; as *granitic gneiss, syenitic gneiss, dioritic gneiss*, etc. The commonest variety is granitic gneiss, with mica or hornblende; the orthoclase and quartz are mingled together, with conspicuous laminæ and folia of the dark mineral.

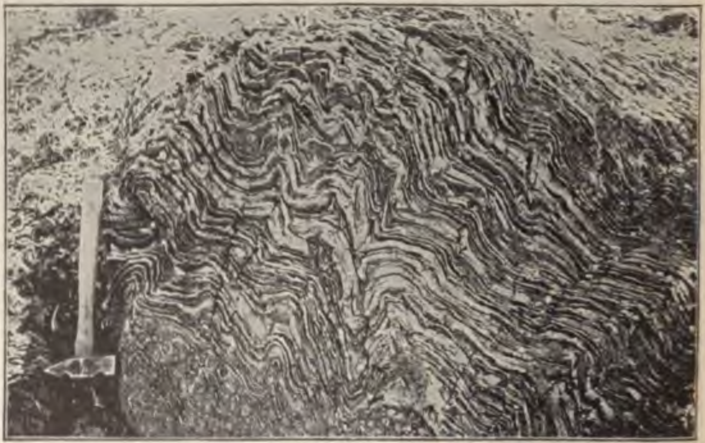

FIG. 130. — Plicated gneiss. (U. S. G. S.)

Most gneisses were generated by the dynamic metamorphism of granite, either before its consolidation or after it had cooled and hardened. Some authorities deny that gneiss has ever been formed from sedimentary rocks, but there is good reason to believe that it sometimes has such an origin, and in certain instances the crushed pebbles of the parent conglomerate are still distinctly visible. Still another series of these rocks are of complex origin, granitic magmas being injected along the foliation planes and into all the crevices of metamorphosed sediments.

Gneisses are widely spread in ancient formations, especially in the most ancient of all, and they cover vast areas in the northern part of North America.

The **Crystalline Schists** are more finely foliated than gneiss, into which they often grade imperceptibly, having very similar mineralogical composition. They have very diverse modes of origin arising from both sedimentary and igneous rocks. Slates, impure sandstones and limestones, as well as felsites, andesites, diabases, tuffs, etc., may all give rise to crystalline schists by thermal or dynamic metamorphism. The varieties are named from their most important ferro-magnesian mineral.

Quartz Schist is a foliated quartzite in which cleavage or fissility has developed into schistosity. The mashing and cementation of the original sandstone may take place at the same time, or the quartzite may be produced by the latter process and subsequently converted into schist by compression.

Mica Schist is principally composed of quartz, muscovite, and biotite, with more or less felspar. By an increase in the quantity of felspar present, and a coarser foliation, they grade into gneiss, and by an increase of quartz they may pass into quartzite and thence to sandstone. Through the phyllites mica schists are connected with the slates, and in another direction, by increase of lime they pass into argillaceous limestones. Mica schists are very largely exposed in New England and southward along the eastern flank of the Appalachian Mountain system.

Hornblende Schist is a foliated rock, consisting of hornblende with a varying proportion of felspar and less quartz. The hornblende schists are, for the most part, derived from the dynamic metamorphism of various basic igneous rocks, the augite being readily converted into hornblende by crushing, but in rare instances they are believed to have had a sedimentary origin. The hornblende schists occur as belts or bosses in metamorphic areas and are largely developed around Lake Superior.

The schists already described are much the most abundant varieties of the group, but there are numbers of others. Thus, we have *talc* and *chlorite schists*, both of which are due to alteration, principally of hornblende schist, and *graphite schist*, which has quantities of that carbonaceous mineral along its foliation planes.

Summary. — Structural geology brings vividly before us the innumerable changes through which the earth's surface has passed and which are recorded in the rocks. The sedimentary rocks, originally laid down under water in approximately horizontal positions, have been upheaved into land surfaces, either without losing that horizontality, or being tilted, folded, compressed, or even violently overturned. Or, they may be fractured and dislocated in great faults and thrusts. These movements we have found to be due to enormous lateral compression set up within the crust of the earth, a compression probably generated by the shrinkage of the cooling globe. Whether folding or faulting shall result from a given compression depends upon the rigidity of the strata, upon the load which overlies them, and the sudden or gradual way in which compression is applied. The results of compression on a large scale are accompanied by certain minor changes not less characteristic. Compressed rocks are cleaved, fissile, or schistose, according to the intensity of the action, and whether the rocks affected are in the zone of flowage or of fracture. These changes may go so far as to completely reconstruct the minerals of the rocks, destroying the old, generating new, and obliterating the original character of the strata. Thus, displacements, dislocations, cleavage, fissility, and dynamic metamorphism are but the varying results of lateral compression, acting under different conditions.

Another class of rocks — the igneous, massive, or unstratified — we found to have penetrated and overflowed the strata, and to have consolidated in the fissures and cavities which they have made for themselves, or to have been poured out freely on the surface. According to the circumstances under which these masses have cooled, the resulting rock is of glassy, porphyritic, finely or coarsely crystalline texture. When solidified as sheets or dikes, the igneous rocks may be folded, faulted, cleaved, or metamorphosed like the strata, and when a region has been long and repeatedly subjected to compression, its structure may become excessively complex, and the metamorphosis of its rocks so complete that not even the most careful examination will suffice to distinguish those rocks which were originally sedimentary from those which were igneous.

Our study has taught us that many of these processes go on deep within the earth's crust, and hence cannot be directly observed, but must be inferred from their results. Very encouraging progress has already been made in this work, but much remains to be done before our knowledge of structure and its full meaning shall be even approximately complete.

PART III

PHYSIOGRAPHICAL GEOLOGY

CHAPTER XVII

LAND SCULPTURE

PHYSIOGRAPHICAL geology is the study of the topographical features of the earth, and of the means by which, and the manner in which, they have been produced.

This subject is primarily a department of physical geography, but is of value to the geologist for the light which it throws upon the historical development of the land surfaces, and upon features of the past which are not recorded in the processes of sedimentation. The geographer endeavours to explain the topographical forms of the land, and, in order to do this, he must show how those forms have originated. The geologist, on the other hand, makes use of the topography to determine what changes have passed over the land, and in what order those changes have occurred. The old method of reading geological history concerned itself merely with the sedimentary accumulations and igneous intrusions. This method has the defect of leaving us without information regarding the changes of land surfaces (except where transgressions of the sea are recorded in unconformities) and the details of mountain-making. The physiographical method supplements this by adding, in part, the required information concerning the land surfaces. Each method is improved and strengthened when we use both of them together, and when we are able to correlate the accumulations of sediments with the denuding processes which furnished the material.

The topography of any land area may be considered as the outcome of a struggle between two opposing sets of agencies: (1) those which tend to upheave the region and thus increase its elevation; (2) those which tend to cut down the land to the level of the sea. The latter comprise the agencies of denudation, or *degradation*, while the former are the *diastrophic agencies*, or simply called *diastrophism*. Two kinds or manifestations of diastrophism may be distinguished: (*a*) *Epeirogenic* (from the Greek *epeiros*, continent), the broad uplifts or depressions of areas, not necessarily accompanied by folding or tilting of the strata; (*b*) *Orogenic* (from the Greek *oros*, mountain), the upheaval of relatively narrow belts of land, caused by the lateral compression of the strata. It is not yet known whether these two processes differ in principle, or whether they are merely different manifestations of the same agencies. Sometimes, indeed, the degrading and diastrophic agencies coöperate, as when the land is depressed instead of upheaved, but this is not the more common condition.

The details of topography are, in large degree, controlled by still a third class of factors, which, however, are passive rather than active; namely, the character, arrangement, and attitude of the rock masses. A partially degraded region in which the rocks are homogeneous will have a very different kind of relief from one in which the rocks are heterogeneous and differ materially in their powers of resistance to the denuding agents. A region of horizontal strata will give rise to very different topographical forms from those which are developed in areas of folded or tilted strata. We must further distinguish between regions whose topography is, in the main, due to constructive processes from those in which denudation has prevailed. Examples of such constructive forms are volcanic mountains, and plains or plateaus formed by widely extended lava flows, plains newly deserted by the sea and due to sedimentation, alluvial plains of rivers, and the mounds, ridges, or sheets of drift spread out by the action of glaciers and of the waters derived from their melting.

The topography of any region is, as we have seen, the resultant of the very complex interaction of many different kinds of factors, and is subject to continual change according to definite laws. Let us suppose, in the first instance, a region newly upheaved from beneath the sea into dry land. The topography of such an area will be *constructional*, due entirely to the processes of diastrophism and accumulation, and characterized by the absence of a highly developed system of drainage by streams. The coastal plain of the middle and southern Atlantic States is an example of such topography but slightly modified.

Next, the processes of denudation begin their work upon the region. The sea attacks the coast-line by cutting it back in one place and building out in another, until a condition of equilibrium is attained. Rivers are established, adjusting themselves to the structure of the underlying rocks, and cutting deep, trench-like valleys, while the atmospheric agencies widen out the valleys, slowly wearing down and washing away the sides and tops of the hills. This is the stage in which we find the greatest degree and variety of relief, and it may be called the stage of *maturity*, as contrasted with the first, which is a stage of *youth*. The continuance of the degrading operations will, if uninterrupted, eventually wear down the region to a nearly plane surface, through which sluggish streams meander, the featureless condition of *old age*. When the process is complete, the country is said to be *base-levelled*.

The term *age* as applied to topographical features does not mean the length of time required for their formation, but merely the stage of development which they have attained. The length of time required to reach a given stage of such development will vary greatly in different regions, in accordance with climatic conditions, the resistance of the rocks, their altitude above sea-level, and similar factors. An area of resistant rocks in an arid climate will be hardly at all affected in the time that a mass of soft rocks exposed to a heavy rainfall will be cut down to base-level.

It seldom, if ever, happens that the topographical development of a region proceeds uninterruptedly through the stages of youth, maturity, and old age. Oscillations of level introduce new conditions and cause the work of denudation to start afresh with renewed energy, or, if the movement be one of depression, it will check the work already in progress. The cycles of development are thus partial rather than complete, and a given region may display topographical forms dating from very different and widely separated cycles. The more resistant rocks retain the features acquired in an earlier cycle, while the weaker and more destructible rocks have already taken on the forms due to a later cycle. A landscape thus often includes features of different geological dates, and it is in the identification of these that the value of the physiographical method to historical geology consists.

In the production of new topographical forms, old ones are more or less completely destroyed, and thus, the farther back in time we go, the fewer subdivisions are recognizable, and only the outlines of the great cycles can be followed. Very ancient features would be quite obliterated in the successive cycles of development, were they not sometimes buried under the sediments of an encroaching sea. A subsequent reëlevation of the area into land, and a stripping away of the covering of newer sediments by the agencies of denudation, will again bring to light the ancient land surface which had been buried for ages.

In Part I we have already studied the agencies of denudation, but there we concerned ourselves principally with the modes of operation of those agencies, and their efficiency in destroying old rocks and in furnishing material for the construction of new. We have now to consider these agencies from a somewhat different point of view; to determine their relative shares in the work of cutting the land down to base-level, and the characteristic forms of land sculpture which they produce at the various stages of their work. There are some differences of opinion among geologists regarding the relative efficiency of the various denuding agents. English authorities, for example, attribute more importance to the work of the sea than do the French or American, who regard the sea as an agency altogether subordinate to those of the atmosphere and running waters. Thus, de Lapparent calculates that the amount of material annually removed from the land by the sea is only about one cubic kilometre, or less than one-fifteenth the quantity carried away by the subaërial agencies.

The Sea. — The work of the sea is confined to the coast-line, which it cuts back by the impact of its waves and currents. Speaking broadly, the waves do but little effective work below the limits of low tide, and advance by undermining and cutting down the cliffs which form the coast. The result of the work is to form a platform covered by shallow water, which is called a plain of marine denudation. As observed in actual cases, these platforms are narrow; for so long as the sea-level remains constant with reference to the land, there is a limit to the effective assault of the waves upon the shore. The water covering the platform is very shallow and only in exceptional cases do the waves have sufficient power to overcome the friction of a wide platform. The material removed from the land, especially the coarser and heavier parts of it, are piled up at the seaward foot of the platform and help to extend it in that direction.

An example of a plain of marine denudation is found on the north coast of Spain, where there is a broad platform between the mountains and the sea, almost perfectly flat. This plain has been uplifted above the sea-level and has been little dissected by the subaërial agents. Narrower platforms, still in process of extension, may be observed on most rocky and precipitous coasts, as those of Scotland, Ireland, and France. Along a slowly sinking coast the platforms may be cut back much farther, for the deepening water prevents the loss of wave power by the friction on a shoal bottom. If, on the other hand, the coast rises at intervals, a series of terrace-like platforms will be cut.

As we shall see in the following section, plains may be produced by the work of the subaërial agencies, and it is often important to distinguish between the plains of submarine and those of subaërial origin. This distinction cannot always be made with certainty, but not unfrequently the plain shows unmistakable signs of the manner in which it was made. In the plain of marine denudation the sediments formed from the waste of the land will be deposited upon the seaward portion of the platform, or upon a lower level of previous formation. Further, this sediment will show by its character that it actually was derived from the material cut away by smoothing the plain, and the whole of it, even its bottom layers, will be of marine origin. In such a plain the advancing sea must have obliterated the stream valleys which had been excavated when the region was land. This obliteration will be performed partly by shaving down the divides, or watersheds, between the streams and partly by filling up the valleys with sediment.

When the region is once more uplifted above the level of the sea, an entirely new system of drainage will be established upon it, determined by the slopes of the overlying cover of newly deposited sediments, and having no reference to the structure and arrangement of the underlying older rocks. These newly established streams may, if the upheaval of the country gives them sufficient fall, cut down through the newer sediments. Indeed, the latter may eventually be swept away entirely by the various subaërial agencies, but the stream courses, which were determined originally by the slopes of that newer sediment, will show little or no adjustment to the structure of the underlying older rocks.

These criteria are useful in identifying those plains which were smoothed by the action of the sea; but when the processes of subaërial denudation have completely dissected the elevated area, all such evidences may be removed and the origin of the plain may become quite indeterminable.

A coast-line newly formed by the elevation of land may be distinguished from one which has stood long at the same level by its unworked character, the first effect of elevation being to produce an even, regular shore-line. This is because the combined effects of erosion and sedimentation tend to make the sea-floor flat and smooth, and an elevation of such a floor to a given altitude must produce an even and regular shore. Nearly the whole west coast of South America is an example of this. On the other hand, a coast which has long stood at the same relative level will show plainly the long-continued action of the sea upon it. What results that action will have will depend largely upon the character and arrangement of the rocks which make up the coast, and whether the shore rises steeply or gently out of the sea. The first effect of the wearing action of the sea is to increase the irregularity of the coast-line, by taking advantage of the weaker spots, with headlands and rocky points formed of the more resistant portions (see Fig. 42). Eventually, however, the headlands are cut back, leaving a submarine platform to mark their former extension, while from this platform may rise islets of erosion, formed by masses of rocks which have better resisted the assaults of the waves. In areas of deposition bars, shoals, and sand spits are thrown up by the winds and waves, running parallel with the coast, and the open beaches take on a crescentic form. Long-continued action of the sea at a constant level thus tends to approximate the even and regular coast-lines of the newly upheaved land. However, an inspection of the *structure* of the coast will reveal the difference.

A coast which has been depressed within a comparatively recent period is one of marked irregularity of outline. The advancing sea fills all the lower valleys, while the higher ridges stand out as headlands and promontories. Isolated hills and mountains are separated from the mainland and converted into islands. The rivers are drowned, their lower courses converted into estuaries, into which side streams empty separately, that before had joined the main stream. A very irregular coast-line, penetrated by many estuaries, inlets, or fjords, and fringed with numerous islands, indicates the submergence of a region already carved into strong relief by the subaërial agencies. Such a coast is admirably typified by that of Maine, where the topography was evidently modelled by subaërial denudation, while a comparatively recent depression has brought the sea over it. The actual form taken by a lowered coast will depend upon the degree and character of the relief which had been attained before the depression, and upon the amount of the subsidence.

The depression of a low-lying coast of small relief is made manifest chiefly in the invasion of the rivers by tidal waters and their conversion into estuaries, examples of which are New York, Delaware, and Chesapeake Bays. These estuaries show by their form that they are river valleys invaded by the sea, and the channel of the Hudson has been traced by soundings to the edge of the continental platform, one hundred miles out from Sandy Hook.

The denuding action of the sea upon a depressed and irregular coast-line is to reduce its irregularities, wearing down the islands, cutting back the promontories, and filling up the bays and more sheltered spots, and, if long enough continued, will result in the same evenness of contour as is produced by the working of an upheaved shore.

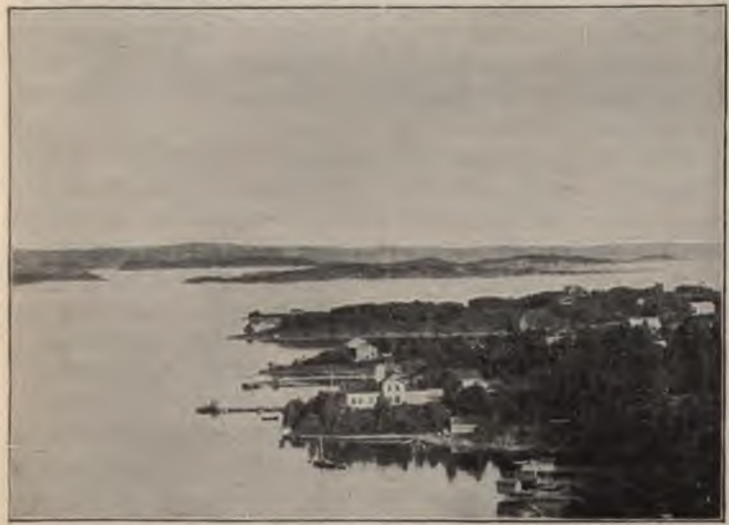

FIG. 131. — Christiania Fjord, Norway. (Photograph by Libbey.)

The Subaërial Agents are those which operate over the entire surface of the land. Their tendency is, in the first instance, to carve out valleys and leave relative eminences standing, and thus to increase the irregularity, or *relief*, of the land. This, however, is merely a temporary stage, and if time enough be granted, these agencies will sweep away the irregularities and plane the entire region down to the base-level of erosion.

Rivers cut down and deepen their channels so long as their beds have sufficient slope and fall. The banks also are undermined, as the current swings from side to side, and frequently fall, thus widening the channel. The sides of the trench, unless removed by other agencies, will be as steep as the nature of the rock material will allow. Unassisted river action will, therefore, cut nearly vertical trenches, which are continually deepened, until the base-level is reached. Examples of such river-cut trenches are the Au Sable Chasm (see Fig. 32) and the inner gorge of the Grand Cañon of the Colorado (see Frontispiece).

The trench-like valley, with nearly vertical sides, is, however, not the usual form of river valley. The atmospheric agencies, the undermining and sapping of springs, landslips, and the like, are continually wearing away the sides of the excavation, the waste thus produced being readily carried away by the stream. As the upper part of each hillside and cliff is that which has been longest exposed to the denuding agencies, the valley will be widened at the top more than at the bottom, and will gradually become widely open, unless the alternation of hard and soft strata be such as to favour the retention of the cliff-like form by undermining.

The rapidity with which the deep and narrow trench is widened into the broad, gently sloping valley will depend upon two sets of conditions. (1) Upon the climate, which is as much as to say, the intensity with which the denuding forces operate. Cañons and narrow gorges are much more frequent in arid regions than in those of abundant rainfall. (2) Upon the resistant power of the rocks. If the valley sides are composed of rocks which yield readily to weathering, the trench will be speedily broadened, while if the rocks offer great resistance to chemical and mechanical disintegration, the gorge-like form will be retained very much longer. This is illustrated by almost any considerable stream, such as the Delaware or the Potomac. In certain places the valley is widely open, while in other parts of the course are deep gorges, as at the Delaware Water Gap and Harper's Ferry. The gorges occur in the places where the stream cuts across hard, resistant rocks, and the open valleys where it intersects softer and more destructible rocks.

Rivers also produce changes in topography by constructional processes, as in their flood plains and terraces, processes which are most notable in the lower parts of the course, and which gain increased efficiency through a subsidence of the region.

Degradation is most rapid on the hillsides which border river valleys, because of the removal of waste by the rivers. Away from the streams the denudation of the country is much slower, because the waste is less readily removed. Those points will longest remain standing above the general level which are composed of the hardest rocks and are farthest removed from the principal lines of drainage.

The subaërial agencies act with the greater efficiency the more elevated the region upon which they operate. Consequently, so long as the region be not again elevated, denudation operates at a continually diminishing rate. The strong relief of hill and valley is carved out with comparative rapidity, but the more nearly the country is reduced to base-level, the more slowly does degradation proceed, and the final stages of base-levelling must be exceedingly slow. Nevertheless, if no renewed upheaval takes place, the loftiest and most rugged land surface must be eventually cut down to that level. The universal and permanent base-level is, of course, the sea; but other local and temporary base-levels may for a time control the development of certain areas. Tributaries cannot cut below the main stream into which they flow; a lake forms the base-level for the streams which supply it, until the lake is removed by draining away or being filled with sediment. Regions, like the Great Basin, whose drainage finds no outlet, may have base-levels either above or below the level of the sea; *e.g.* the surface of the Dead Sea of Palestine is 1308 feet below the Mediterranean.

It is perhaps a question whether any large region has ever remained stationary (with reference to the sea-level) for a sufficiently long time to be absolutely base-levelled. On the other hand, there is abundant evidence to show that such areas have been worn down to a low-lying, featureless surface, with only occasional low protuberances rising above the general level. Such a surface is called a *peneplain*, and represents what is usually the final stage of a cycle of denudation. Here and there an isolated peak may remain high enough to deserve the name of mountain, which owes its preservation to the exceptionally resistant nature of the rocks of which it is composed, or to its exceptionally favourable position with reference to the drainage lines. A renewed upheaval of the peneplain will begin another cycle of denudation, revivifying and rejuvenating all the destructive agencies, and valleys and hills will be carved out of the approximately level surface. In a peneplain dissected by the revived streams the sky line of the ridges is notably even, and all the heights rise to nearly the same level. Differences of level are, however, frequently produced by a warping process, which may accompany the upheaval, raising some portions of the peneplain to greater heights than others. Excellent examples of reëlevated and subsequently dissected peneplains are the uplands of southern New England and the highlands of New Jersey.

One agent of subaërial denudation has such a characteristic and peculiar method of work that it requires a few words of separate consideration. This agent is the glacier. In Chapter VI these peculiarities were described, and it will suffice here to recall them briefly. A glacier, in those parts of its course where deposition does not occur, sweeps away whatever previous accumulations of soil and loose débris it may encounter, laying bare the rock. The rocks, hard and soft, are ground down, marked with long parallel scorings, grooved, and polished. The valley in which an Alpine glacier flows was made in the first instance by the atmosphere and running water, but the moving ice has modified it in several particulars. A glacial valley is widened, losing the V-shape and taking on more the shape of a U. The longitudinal slope of the valley is less continuous than in one made entirely by water, being broken by ridges or escarpments of polished rock, behind which are depressions. These depressions may be converted into lakes when the glacier has retreated, but it is still a question how far a glacier is able to excavate solid rock. The *fjords* of Norway are glaciated valleys which have been invaded by the sea.

An equally characteristic kind of topography is due to the constructive work of glaciers. The terminal moraine of a valley glacier or of the lobes and tongues given off by an ice-sheet, surrounds the end of the ice, with its concave slope directed up the valley, thus forming a more or less crescentic dam. A glacier retreating, but with stationary pauses, builds up one of these moraines at each halt, or if the retreat be rapid and continuous, the material is spread over the abandoned ground and is frequently worked over by the waters derived from the melting ice into stratified deposits. The morainic dams often pond back waters into lakes. Kettle moraines, which have deep conical depressions in them, are believed to be due to the isolation of masses of débris-covered ice, left behind by the retreating glacier, and the subsequent melting of these isolated masses has formed the depressions. To what extent material can gather *beneath* a moving mass of ice is still an open question, but the vanished ice-sheets have left over much of their former courses great masses of drift, spread like a mantle over the ground and filling up the valleys. In the northern United States countless stream valleys have thus been obliterated.

In considering glacial topography, then, we have to deal with the work of erosion and of deposition by the ice, each of which produces effects peculiar to itself. In the *central zone* of the ice-sheet, where the ice remained longest, it had its maximum thickness and destructive efficiency. Here the principal work is that of erosion, and when the ice has retreated, we find great areas of naked, striated, and polished rocks, abounding in *roches moutonnées* and in lake-filled rock basins. In the *peripheral zone* of the ice-sheet, the ice was thinner, more sluggish in movement, was subject to episodes of advance and retreat, and did not remain for so long a time. Here the work was prevailingly that of deposition, and the resulting topography has little relief, and that relief is very irregular. Sheets of drift, morainic mounds and dams, which enclose small lakes or marshes, erratic blocks, and quantities of water-worked and more or less stratified drift are the characteristic features. The confused and irregular, but low relief which marks the outer zone of the ice, is generally succeeded by a plain of sand or gravel, the *overwash plain*, produced by the débris-laden waters which escaped from the front of the ice.

Kames, Eskers, and Drumlins. — These are peculiar forms of glacial accumulations which are found in the peripheral zone. *Kames* are hillocks or short ridges of stratified drift, formed by the deposition of materials from subglacial streams as they escape from under the margin of the ice. *Eskers* or *Åsar* are long, winding ridges of sand and gravel, which may have considerable height and which follow the general direction of the moving ice. Several eskers may join one another, just like a stream and its tributaries. The accepted explanation of these ridges is, that they mark the beds of streams which flowed upon or under the ice, near its edge; the sand and gravel were laid down in channels or tunnels in the ice and thus were prevented from spreading out into a flat sheet. When the ice retreated, the stream deposits were left standing as ridges. Kames and eskers are common in glaciated regions, and are well displayed in New England and in central New York. The latter are probably forming under the Malaspina glacier now. (See p. 157.) *Drumlins* are elliptical hills or mounds (sometimes 200 feet high), which are arranged in lines coincident with the direction taken by the moving ice. Drumlins are not at all or only partially stratified, and were formed by the combined action of ice and water or by ice alone near the margin of the ice-sheet. Thousands of them exist in the northern United States, especially in New England, Wisconsin, and Minnesota.

A glaciated topography is one marked by rounded, flowing outlines, in contrast to the craggy hills of regions which have never been smoothed by ice. In one way or another, a glacier leaves many depressions and basins in its tract, which, when the ice has retreated, become filled with water and form lakes. A glaciated region is preëminently a region of lakes.

Topography conditioned by the Arrangement of Rocks

While the final effect of the subaërial denuding agencies is to sweep away all relief, and to cut the land surface down to low-lying base-levels or peneplains, yet in the process great irregularities are produced by the more rapid removal of some parts than of others. The topographical forms generated by this differential erosion vary much according to circumstances. We have already considered some of these differences with regard to the agencies which have produced them. Now we have to examine the differences with a view of learning how topographical forms are determined by the character and arrangement of the rocks which are undergoing degradation.

When a peneplain or plain of marine denudation is lifted high above sea-level, without folding or steep tilting of the strata, streams are soon established upon the new land, and proceed to cut deep trenches across the plateau, which are gradually widened out under the influence of weathering, and the arrangement of hard and soft rocks finds expression in the resulting forms. If the surface layers resist weathering, the plateau will be gradually dissected into flat-topped *mesas* and table-mountains; while if the whole mass of rocks be easily destructible, they weather down into dome-shaped and rounded hills, which are smallest at the top, the part longest exposed to weathering. The wild and grotesque scenery of the Western bad lands, with their chaos of peaks, ridges, mesas, and buttes, is merely the result of the differential weathering of horizontal strata, some beds and parts of beds yielding more readily than others. If a series of more resistant beds underlies a mass of softer strata, a change in the topographical forms will occur when the underlying harder rocks are partially exposed. In the soft rocks the valley sides have gentle slopes, but when the harder mass is penetrated, the slopes become steep, or even vertical. When hard and soft strata alternate in a valley wall, the harder beds form cliffs. This is accomplished by cutting away the softer beds and thus undermining the harder ones, until the latter can no longer support their own weight, and masses fall from the face of the cliff, thus maintaining the verticality. The talus blocks form a slope, connecting the successive cliffs by gentler inclines. The Uinta Mountains in northern Utah are formed by a great anticlinal arch, so broad and gently curved that in a given section the strata appear almost horizontal. Out of these immensely thick and nearly level masses the atmospheric denuding agencies have carved an infinite and most picturesque variety of peaks, pinnacles, columns, and amphitheatres, while the streams have cut profound and gloomy cañons. Vast talus slopes remain to indicate the amount of destruction.

Inclined or tilted strata give rise to a different class of topographical forms. If, as is generally the case, harder and softer strata alternate, the latter will be swept away more rapidly than the former, which are left standing as ridges or cliffs, the height and steepness of which are determined by the thickness and inclination of the more resistant rocks. In case the strata are steeply inclined, a succession of hard beds alternating with soft will give rise to a series of ridges and valleys, the slopes of which depend upon the angle of dip. If the beds are standing in a vertical position, the two slopes of each ridge will be nearly equal, the hard strata forming the backbone of the ridge and the softer ones the sloping sides. As the inclination departs from verticality, the more unequal do the two slopes of each ridge become the longer and gentler one being in the direction of the dip. Ridges and valleys of this class are beautifully exemplified in the Appalachian Mountains. Figure 25 shows Kittatinny Mountain, through which the Delaware River has cut the famous Water Gap; the crest of the ridge is formed by very hard and indestructible sandstones and conglomerates, while the valley is in slates.

In gently inclined strata the abruptly truncated and cliff-like outcrops of the hard strata are called *escarpments*, and follow, with some irregularities and sinuosities, the strike of the beds. Whether the general course of the escarpment shall be straight or curved will, therefore, be determined by the constancy or change in the direction of the dip; for, as we have already learned, the strike changes

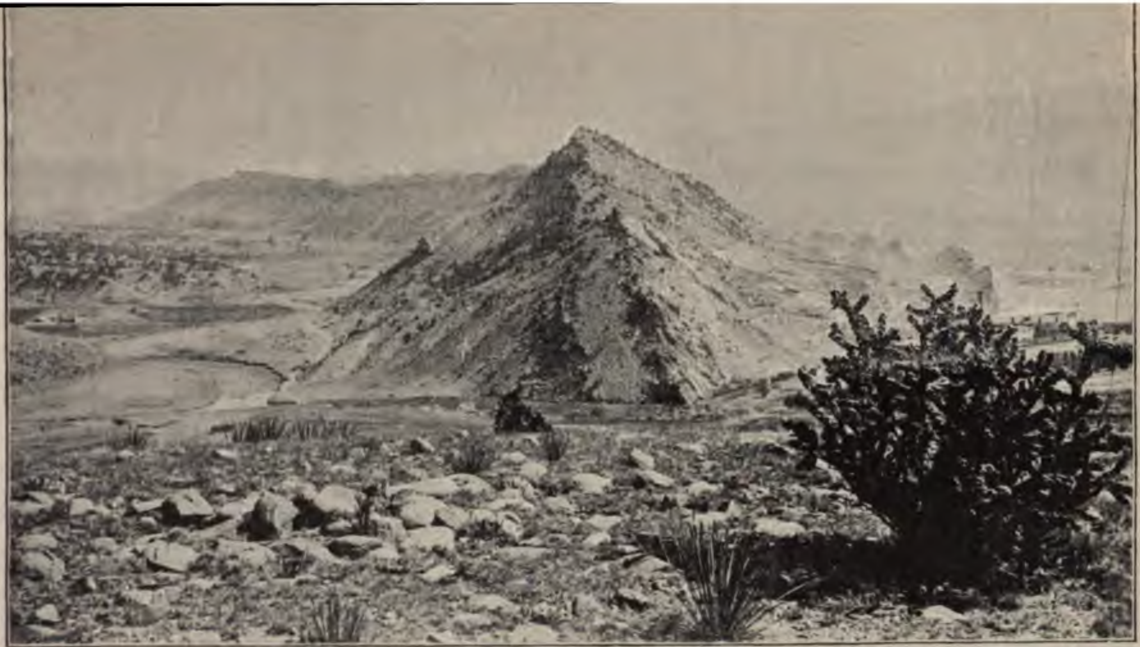

FIG. 132.—Hog-back, near Golden, Col. An escarpment formed by the descending limb of a monoclinal fold, of which the upper horizontal limb has been eroded away.

with the dip, always keeping at right angles to the latter. The upper surface of the gently inclined hard stratum may be completely exposed by the stripping away of the softer overlying mass, and then the slope of the ground is the same as that of the resistant stratum and is called a *dip slope*. A series of gently inclined strata, made up of alternating harder and softer beds, will thus give rise to parallel ridges and valleys, or escarpments and dip slopes, according to the completeness with which the softer beds are removed and the harder ones exposed. A magnificent example of such escarpments and slopes is displayed in the high plateaus of Utah and Arizona, where the dip slopes are from 20 to 60 miles broad and the escarpments 1500 to 2000 feet high. The amount of denudation involved in the production of these vast amphitheatres staggers belief, though there is no escape from the enormous figures.

Under the influence of denudation escarpments are continually though slowly receding, being cut back in the direction of the dip. Rain and frost act directly upon the hard beds, but work more effectively by cutting away the softer beds below and thus undermining the hard strata, causing them to fall. The fallen masses are gradually disintegrated in their turn and washed away into the water-courses. The escarpments may follow a relatively straight or a very sinuous course. Sinuosities, when present, are commonly due to the presence of springs, which undermine the escarpments and, by the recession of their heads, excavate the line of cliffs into bays and amphitheatres. A sinuous escarpment is more rapidly cut back than a straight one, because, in addition to the coöperation of the springs, it offers a larger surface to the attack of the destructive agencies. Every step in the recession of an escarpment lowers the ridge and brings it nearer to base-level, because the direction of retreat follows the line of dip, which carries the beds down to base-level with a rapidity determined by the angle of dip. A steeply inclined bed needs to be cut back only a short distance, when it will be reduced to base-level, whereas a bed dipping very gently remains above base-level for very long distances. Of course the general elevation of the whole region above base-level is also an important factor in determining the amount of work to be done.

For reasons that will appear later, we assume that when denudation began its work upon a region of inclined strata, that region was a sloping plain, or peneplain, formed by the outcropping *edges* of the strata. The first lines of drainage established would necessarily follow this slope, and the first valley or valleys cut would be across the strike of the beds, trenching both hard and soft beds. Such valleys are called *transverse* and the streams which flow in them, *transverse streams*. A second series of valleys will be excavated along the strike of the softer beds, giving *longitudinal* val-

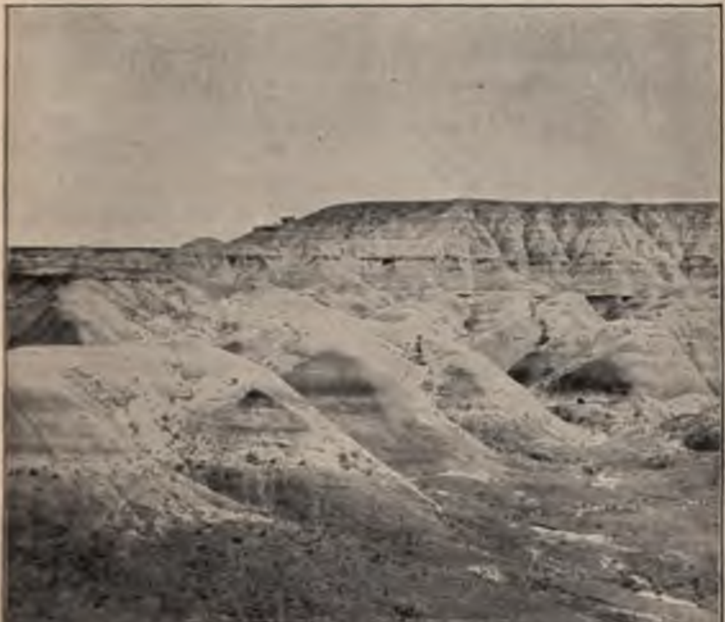

FIG. 133.—Mesa and round-topped buttes, exhibiting unconformity and change in character of the strata. Bad lands of South Dakota.

leys and streams. In such a longitudinal valley, following the strike of a mass of soft strata, the stream which occupies it will tend to flow along the foot of the escarpment formed by the outcrop of hard strata, and to shift its course laterally in the direction of the dip, cutting away the soft beds in which it flows, and undermining the hard escarpment. Such a stream is a potent agent in causing the recession of the escarpment and may remove large areas of both hard and soft strata.

The steep ridges, or "hog-backs," which occur among the foothills of the Rocky Mountains in Colorado, show interesting examples of streams flowing along the strike of inclined strata, though the ridges are themselves not formed quite in the way already described. They are composed of the steeply dipping limbs of *monoclinal* folds, of which the upper horizontal limbs have been removed by denudation (Fig. 132).

Folded Strata. — A region of folded strata is, in the first instance, thrown into a series of ridges and valleys, the ridges formed by anticlines and the valleys by synclines. If the folding be of moderate degree, so as to produce undulations of sweeping and gentle curves, the tendency of denudation is to reverse the original topography and convert the anticlines into valleys and the synclines into ridges. This apparently paradoxical result is found, when examined, to be natural and simple enough. The crests of newly formed anticlines have been subjected to tensile stresses which open the joints in the strata and render them an easy prey to the denuding agents. The surface of the synclines, on the contrary, has been tightly compressed, and their joints are closed by crowding. Aside from this, another factor tends to produce the same result. In a folded series of alternating harder and softer beds denudation is most rapid on the exposed anticlines, and in them the hard strata are first reached and cut through. When an underlying mass of soft strata is reached, they are rapidly trenched into valleys which may soon be excavated below the level of the synclinal troughs.

If the folds originally made by the force of lateral compression be steep and high, as in mountain ranges, the anticlines persist longer as ridges, but the wearing away of their summits gives rise to subordinate ridges and valleys within the limits of each anticlinal arch. Here also the ridges are the outcropping harder beds, and the valleys are cut in the softer ones. Even in mountain ranges denudation may reverse the original structural topography and give rise to anticlinal valleys and synclinal mountains.

If a region of folded rocks has once been planed down to base-level or to a peneplain, and then reëlevated and subjected to denudation, the resulting topography will be determined by the same laws. Indeed, this is the method in which regions of tilted or inclined strata are produced, for, as we saw in Chapter XII (p. 232), inclined beds are generally parts of truncated folds. In such regions drainage is first in accordance with the slopes of the planed and tilted surface, but as denudation proceeds, the structure and arrangement of the rocks make themselves felt, and bring about changes and adjustments of the drainage to the structure, as will be more fully explained in the following chapter.

The combined action of the displacement and dislocation of the strata, on the one hand, and of denudation, on the other, often results in the formation of disconnected patches of rock which, according to their geological relations, are called *outliers* and *inliers*. An *outlier* is an isolated mass of rock, like an island, which has been cut off by denudation from its former connections. Outliers are sometimes scores of miles from the nearest mass of the same strata, and they stand as monuments which show, partially at least, the former extension of the eroded beds. An outlier rests upon the underlying strata, and when *viewed on a map*, which brings all projections down to one plane, is surrounded by beds which are geologically older than itself. Outliers are almost always composed either of horizontal strata, or of isolated synclines, for an isolated anticline would soon be swept away by denudation, the dip coinciding with the slope of the surface, an arrangement very favourable to landslips and rapid erosion.

n *inlier* is produced by the truncation of an anticline or a me, exposing an area of a lower stratum surrounded by strata ich are geologically above it. If the isolated mass be brought the surface by faulting, it is called a faulted outlier or inlier, ccording as it is surrounded by older or younger beds. A faulted outlier is on the downthrow side of the dislocation and a faulted lier on the upthrow side.

CHAPTER XVIII

ADJUSTMENT OF RIVERS

Rivers are among the most powerful of the agents of topographical development, and it is important to understand something of their modes of change and adjustment. These changes are sometimes exceedingly complex and puzzling, for rivers do the most unexpected things in what seems an utterly capricious and whimsical way. We often see rivers breaching hills and even vast mountain ranges, cutting their way through enormous obstacles, which a slight deviation from their course would, seemingly, have enabled them to avoid. They apparently choose the difficult and shun the easy path. The general explanation of these paradoxical results is, that the river began its flow when the topography was entirely different from its present state of development. It is this fact which renders the rivers such valuable aids to the geologist in his attempts to reconstruct the past, for the apparent whims and caprices are really the necessary results of law.

A river has its stages of development, youth, maturity, and old age, just as has a land surface, each stage displaying its characteristic marks. When a new land is upheaved, the first drainage lines established upon it are, as we have already learned, determined entirely by the slopes of the new surface and are called *consequent streams.* In its earliest stages a river can drain its territory or basin in only imperfect fashion, and whatever depressions exist in the surface of the new land are filled up with water and form lakes. Tributaries are much fewer than in later stages of development; the divides between the tributaries are obscurely marked, and in plains these divides are broad areas, not lines. The Red River of the North is an example of a stream in a very youthful stage, which flows across the level floor of an abandoned lake. In this plain the divides between the streams are so wide and flat that water gathers on them after heavy rains, having no reason to flow in one direction rather than another.

As the river system becomes somewhat older, the stream channels are deepened, the larger ones being cut down to base-level, and if the region be one of considerable elevation, deep gorges and cañons are excavated. If the streams flow across strata of different hardness, waterfalls result where a hard ridge crosses them, but in the main stream these cascades and rapids are ephemeral and soon removed by the stream's wearing down the obstacle. On the head-waters of streams, however, waterfalls may persist for a long period. The river valleys are widened out by atmospheric denudation, and channels are formed on their sloping sides, which gradually grow into side valleys. The lakes are for the most part drained or silted up, only the more important and deeper ones remaining, while the system of tributary streams and rills is greatly expanded. A mature river system is characterized by the complete development of its tributaries and drainage, so that every part of its basin is reached by the ramifying channels. The waterfalls have disappeared, except near the stream-heads, and the stream channels have sought out and utilized every weakness in the strata, adjusting themselves to the structure of the rocks and the alternations of hard and soft beds.

The complete network of streams has enlarged the valley surfaces, which increases the rate of destruction and brings to the river a greater load of sediment to carry. In maturity the river receives its maximum load, sometimes so great that the lower reaches of the main stream are unable to transport it all, and spread the excess out over the flood plain. The channel of an overloaded stream may be so raised and banked in by its own deposits, that some of the tributaries are deflected and made to run for some distance parallel to the main stream, perhaps even reaching the sea independently. An example of this is the Loup Fork of the Platte in Nebraska. "The Platte flows there upon a ridge of its own creation. The Loup comes down into its valley and flows parallel with it for many miles." (Gannett.)

The final stages of river development are reached when the base-level is attained, and the drainage basin reduced to a peneplain by the combined action of the streams and weathering. The flood-plain deposits may now be partially or completely removed, for the main trunk no longer receives an excessive load, and hence it is able to carry away some of that sediment which it had previously deposited. With its drainage basin smoothed down into a peneplain, the river's work is done; it has reached old age.

The course of river evolution above described is the ideal cycle of development which, however, may be and generally is interrupted by diastrophic movements. An elevation of the region may simply rejuvenate the streams and start them afresh upon a career of wearing down the land. But if accompanied by extensive warping or folding of the rocks, the drainage system of the entire region may be revolutionized. A depression of the region will have the contrary effect, checking or stopping the work in which the streams were engaged, drowning their lower reaches and converting them into estuaries. A lowered land surface has less material to lose before it is reduced to base-level, but the work of denudation is accomplished more slowly.

In a newly formed mountain region the drainage system is at first consequent upon the slopes produced by folding, the principal streams flowing in the synclinal troughs and passing from one syncline to another at the points where, owing to the descending pitch of the folds, the anticlines are lowest. The principal valleys are thus longitudinal. Such a system of drainage is exemplified in the Jura Mountains of Switzerland, a region where the topography is still dominated almost completely by the regular folds which form anticlinal ridges and synclinal valleys. In very ancient regions of folded rocks, on the other hand, the original longitudinal valleys may become altogether insignificant in comparison with the transverse valleys excavated by the streams.

When it was first suggested that rivers had cut their own valleys and had not merely taken possession of ready-made trenches, it was objected that such an explanation required many streams to begin their course by flowing up hill. It is very common to find a stream flowing across a region, cutting its way through ridge after ridge, instead of following the easy path of the longitudinal valleys. This is just what the principal streams of the northern Appalachians, such as the Delaware, the Susquehanna, and the Potomac have done, and at first sight, their course is very difficult to explain. Without going very far back into the history of these mountains, we may simply state that the ridges through which the rivers named have cut are the remnants of a reëlevated and dissected peneplain, across which the streams flowed to the sea, cutting transverse valleys that were rapidly deepened into gorges. On the soft strata longitudinal valleys were opened out which, however, were formed after the transverse streams and could not be deepened faster than they, because the main stream flowing in each transverse valley gave a temporary base-level for the tributaries flowing in the longitudinal valleys. The hard beds were sawed through by the descending streams, but elsewhere these beds stood up as ridges, and thus the ridges are also younger than the streams. The mystery disappears at once, if we simply remember that the transverse streams began their flow upon a sloping plain above which the present ridges did not project.

Antecedent Rivers. — Another way in which rivers have been enabled to cut their way through opposing ranges of hills and even mountains, is by occupying the district before the hills or mountains were made. Such streams are called *antecedent* and are defined as "those that during and for a time after a disturbance of their drainage area maintain the courses that they had taken before the disturbance." (Davis.) The simplest case of antecedent drainage is where an area is uplifted without deformation and without changing the direction of the slopes. Under such circumstances all the streams retain their old channels, and simply gain renewed power to cut them into deeper trenches, down to the new base-level. Such streams are said to be *revived*. Even if the upheaval be accompanied by folding or deformation, one or more of the streams may persist in its ancient course, provided the folding be very slow and gradual, so that the river is able to cut down through the obstacles which are raised athwart its course. A revolving saw cuts its way through a log which is pushed against it, so the river cuts its way through the rising barrier. If the latter be raised faster than the river can cut, then the stream will be dammed back into a lake, or will be diverted to a new course.

A famous example of what many authorities believe to be an antecedent stream is the Green River in Wyoming and Utah. Entering from the north, the river cuts its way in a winding course through the great mountain barrier of the Uintas in a remarkable series of cañons, although by turning a short distance to the eastward, it might have found a path several thousand feet lower than the one which it has chosen. Even more extraordinary is the Yampa, which flows in from the east, and though a slight southerly deflection would have brought it to the Green on the plains south of the mountains, it cuts its profound gorge along the axis of the uplift, meeting the Green in the heart of the range. The strange behaviour of these two streams is usually explained by regarding them as antecedent, occupying nearly the same channels as they had before the mountains were upheaved. The uplift was so gradual that the rivers cut through the barriers as fast as the latter were raised. This explanation is not accepted by all the observers who have examined the region, some of whom explain the phenomena by the theory of superimposed drainage, described in the following section. Several rivers in the Alps and Himalayas, which rise in the inner part of the ranges and cut their way out through deep chasms, are believed to be antecedent.

Superimposed Rivers. — A region newly upheaved from the sea is covered to a greater or less depth with marine deposits which may lie unconformably upon a foundation of older rocks of entirely different character, arrangement, and structure. The system of drainage established upon the new land is at first *consequent* upon the initial slopes of the region. As the streams cut their trenches through the overlying mantle of newer strata, they encounter the older rocks below, first laying bare the higher ridges of the latter, which will cause waterfalls and rapids. The upper Mississippi has in many places excavated its channel through the surface sheet of glacial drift and is now engaged in eroding the ancient crystalline rocks which the drift had covered. When the stream has everywhere cut through the newer rocks, its course will be seen to have no relation to the structure of the older rocks which it is now trenching. If, as frequently has happened, denudation has stripped away almost all the newer strata, the drainage of the country seems to be quite inexplicable and to be arranged without any reference to the structure of the rocks across which the streams flow. Such a system of drainage is said to be *superimposed*, *inherited*, or *epigenetic*.

Subsequent Streams. — As a river system approaches maturity, and as the drainage of the area becomes more complete, it will increase the number of its branches. Those branches which were not at all represented in the youthful stages of the system, and are opened out along lines of yielding rocks, are called *subsequent*, and all streams will develop more or fewer of such branches as they advance to maturity.

Adjustment of Streams. — However the streams of a district may have been established in the first instance, whether they were consequent, antecedent, or superimposed, they are liable to changes more or less profound and far-reaching. These changes, which belong to the normal development of the drainage system and are not dependent upon diastrophism, are due to adjustment of the streams to the rock structure of the district, the streams searching out the lines of weakness and least resistance, and everywhere taking the easiest path to their destination. The upstream extension of branches and the shifting of the divides result in the *capture* of streams, or parts of such, by others more favourably situated, one master stream gradually absorbing many smaller ones which had originally been independent.

A divide, or water-parting, between two streams is gradually shifted by the lengthening of the more favourably situated stream, or of one of its subsequent branches. This more favourable situation may be because it has a shorter course and greater fall, giving a swifter flow, or because it flows at a lower level, giving greater fall to its tributaries, or because its course is through soft and easily eroded rocks, while its rival is embarrassed by hard rocks and ledges. Another favourable circumstance which may decide between streams otherwise equal is given by the attitude of the strata. In regions of inclined strata, as we have already learned, the escarpments formed by outcropping ledges of harder rocks tend to migrate in the direction of the dip. As such escarpments frequently form divides between minor streams, the stream towards which the escarpment migrates will be at a disadvantage. This shifting of divides is a very slow process, but after a long time of insidious advance the actual capture and diversion of part of a stream may be quite suddenly effected.

Stream capture may be effected in a great variety of ways, but a few examples must suffice. We may, in the first place, suppose two neighbouring streams following roughly parallel courses, but, owing to the original conformation of the region, flowing at different levels. The stream that flows at the lower level will allow greater fall to its tributaries, which will thus work upward more rapidly. One of these tributaries will eventually work its way through the divide and tap the rival stream, all of whose waters above the point of tapping will be diverted to the main stream which flows at the lower level.

Another method of stream capture is well illustrated by the Delaware, the Potomac, and other transverse rivers which have cut deep gorges through the Appalachian ridges. Suppose two parallel transverse streams flowing across a gently sloping peneplain which is composed of tilted rocks of different degrees of hardness. In the manner already explained (p. 317) these streams cut gorges through the ridges of hard rock, while longitudinal valleys are worn out along the strike of softer strata, which valleys are occupied by tributaries of the transverse streams. If one of the two transverse streams be considerably larger than the other it will saw its way through the hard ridges at a correspondingly faster rate and establish a lower base-level for its tributaries. One of the tributaries with its more rapid fall will be thus enabled to shift its divide at the expense of a branch of the rival transverse stream, capture it, and by reversing the direction of its flow draw off the waters of the smaller main stream above the point where its captured tributary entered it. Or, a tributary of the larger main stream may push its way up a longitudinal valley until it taps and diverts the smaller transverse stream without the intermediation of any tributary of the latter. Examples of both of these varieties of capture may be found among the Appalachian rivers; an excellent illustration of the latter method is given by the Potomac and Shenandoah.

When the Potomac was beginning to cut its gap through the Blue Ridge at Harper's Ferry, a smaller stream, Beaverdam Creek, was cutting a similar gorge through the same ridge a few miles to the south. The Shenandoah was then a young and short tributary of the Potomac, which it entered from the south, flowing through the longitudinal valley which was opening along the strike of the softer strata to the west of the Blue Ridge. As the Potomac is much larger than Beaverdam Creek, it cut its gap much more rapidly, thus giving a steep and swift course to the Shenandoah. The latter pushed its way up the longitudinal valley until it tapped Beaverdam Creek and captured its upper course, diverting its waters to the Potomac. Beaverdam Creek no longer flowed through the gorge which it had cut in the Blue Ridge and which was thus abandoned and became a "wind gap," the beheaded Beaverdam now rising to the eastward of the abandoned gorge. This gorge is known as Snickers Gap. The great number of wind gaps in the Appalachian ridges shows how frequently the capture and diversion of smaller streams by larger ones has been accomplished among those mountains.

Figures 134 and 135 show two stages in the evolution of a river system. Figure 134 represents the first stage, in which several transverse streams, *a*, *c*, *e*, *f*, *g*, are breaching the escarpments indicated by shaded lines. Of these streams *c* carries the most water, and will therefore deepen its gorges through the hard ridges more rapidly than the others, and give its tributaries the advantage of a greater fall. In the second stage (Fig. 135), *c* has captured the upper courses of all the other streams except *g*, which has not yet been reached. The branch *l* has captured *a*, beheading it, *divert-*

ing the portion *a''* and *reversing* the portion *a'*. Similarly, *m* has captured and divided *e*, *n* has done the same with *b*, and *p* with *d*, while *g* must eventually suffer the same fate. Wind gaps will be left in the ridges where the captured streams once crossed them.

In regions of folded rocks thrown into a series of parallel anticlines and synclines, the process of adjustment may become exceedingly complicated. Suppose an original consequent stream flowing in a syncline of hard rock considerably above base-level, whose subsequent branches have opened out valleys in softer rocks along the crests of the anticlines, where the harder surface stratum is first cut through. The extension and junction of these subsequent branches may offer a more advantageous course than the hard syncline, and cause the latter to be wholly or partially deserted. The streams originally flowing in the synclinal troughs may gradually be shifted to the degraded anticlines which, as we have seen, are wasted away more rapidly.

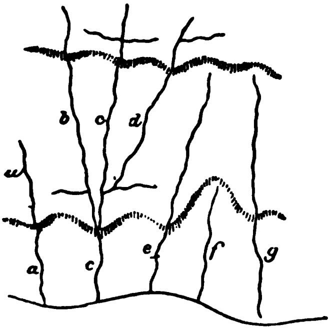

FIG. 134. — Evolution of a river system, first stage. The shaded lines represent escarpments of hard rock. (De Lapparent.)

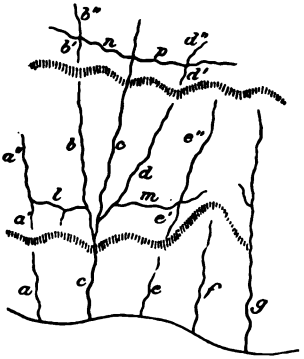

FIG. 135. — Evolution of a river system, second stage. (De Lapparent.)

A thoroughly mature drainage system is characterized by a complete adjustment of its streams to the structure of the rocks. The rivers as finally established are thus apt to be a patchwork of streams captured and diverted, and the result of adjustment is the production of a system often radically different from the original one. Even after a river system has become maturely adjusted, a reëlevation of the country may produce a new and entirely different adjustment, by changing the relation of the folds and outcrops of hard and soft strata to the base-level. A region of great antiquity which has repeatedly been worn down and reëlevated will have experienced many revolutions of its drainage systems. In the difficult work of deciphering these complex histories all the indications of abandoned stream channels must be carefully examined. Some of these, like gravel deposits or wind gaps, are easy to find and to trace out, but subsequent denudation will frequently have removed the gravels and otherwise masked the old stream courses. In rocky regions a welcome indication of ancient stream courses is often given by *pot holes*, which are deep, circular, well-like openings excavated in the rock, and wherever they occur was once the bed of a stream. A pot hole is made by the gyration of stones which are whirled around by an eddy in the current or at the foot of a waterfall The conditions must remain constant for some time for the hole to be cut to any depth, some of them being as much as twenty feet deep.

Accidents to Rivers. — This term is employed to express the interruptions which hinder or prevent the normal development of a river system. The diastrophic changes and their effects we have already considered, but there are others which should be mentioned. A change of climate from moist to arid greatly interferes with the development and adjustment of a river system. Many stream channels are abandoned and others are occupied only after rains, while the reduced flow in the permanent streams diminishes their erosive powers. Large areas, like the Great Basin region, may have no outlet to the sea, because the mountain streams all lose themselves in the desert sands. Lake Bonneville (see p. 146) had an outlet until the increasing dryness of the climate so lowered its waters that the outlet could no longer be reached. evaporation exceeding inflow. Great lava flows may obliterate the drainage system of a region and compel the establishment of an entirely new one, as has happened in southern Idaho and southeastern Oregon, a region of exceedingly immature topography and drainage. Extensive ice-sheets, by spreading a thick mantle of drift which fills up the valleys, may produce the same effects as lava flows, except that the drift is more easily removed. In the northeastern United States many streams have been displaced by the sheets of glacial drift, and forced to seek new channels at a comparatively recent date; they still preserve all the signs of youth, such as deep, trench-like gorges (see Fig. 32), waterfalls, and rapids. The larger rivers have, for the most part, been able to reoccupy their old valleys, but the smaller streams have generally been compelled to excavate new channels.

CHAPTER XIX

MOUNTAIN RANGES — CYCLES OF EROSION

THE term *mountain* is somewhat loosely employed for any lofty eminence, and the distinction between mountains and hills, as ordinarily made, is principally a question of mere height. Some so-called mountain peaks and ridges are merely the portions of dissected plateaus left standing, such as Lookout Mountain and Missionary Ridge in Tennessee, and the Allegheny Front in Pennsylvania. Such mountains usually have flat tops (table mountains), are composed of strata which are nearly or quite horizontal, and owe their existence either to their being composed of more resistant rocks than the denuded parts of the plateau, or to their favourable situation with reference to the drainage lines. Another type of mountain is the volcanic, which is usually an isolated cone and may be built up to great heights; it is simply the accumulation of volcanic material which has been piled up around the vent. Typical mountain ranges and chains differ materially from either of these classes, both in their structure and their mode of origin. Before proceeding to discuss the origin and history of mountains, it will be necessary to define the terms to be used.

A **Mountain Range** is made up of a series of more or less parallel ridges, all of which were formed within a single geosyncline (p. 236) or on its borders. The ridges are separated from one another by longitudinal valleys and may be formed either by the successive folds or by denudation within the limits of the folds. In the latter case the outcropping harder strata make the ridges. A mountain range is always very long in proportion to its width, and its ridges have a persistent trend. These features distinguish a true range from the ridges cut out of a plateau by denudation. The Appalachian range, the Wasatch, the Coast Range, are examples of typical mountain ranges.

A **Mountain System** is made up of a number of parallel or consecutive ranges, formed in separate geosynclines, but of approximately similar dates of upheaval. The Appalachian system comprises the Appalachian range, running from New York to Georgia, the Acadian range in Nova Scotia and New Brunswick, and the Ouachita range in Arkansas. Each of these ranges was formed in a different geosynclinal, but at the same geological date, and they are consecutive, having a common direction.

A **Mountain Chain** comprises two or more systems in the same general region of elevation, but of different dates of origin. The Appalachian chain includes the Appalachian system, the Blue Ridge, the Highlands of New Jersey and the Hudson, a system of different date, and the Taconic system of western New England, which was not formed at the same time as either of the others.

A **Cordillera** consists of several mountain chains in the same part of the continent. Thus, the chains of the Rocky Mountains, Sierra Nevada, Coast Range, and their prolongations in Canada, together make up the Rocky Mountain or Western Cordillera.

From these definitions it will appear that the mountain range has a unity of structure and origin which fits it especially for study. If the structure and history of the ranges be understood, the systems and chains will offer little additional difficulty.

A mountain range (disregarding, for the present, certain exceptional cases) consists of a very thick mass of strata, which are much thicker in the mountains than the same strata in the adjoining plains. In the Appalachian range, for example, the stratified rocks are nearly 40,000 feet thick, but on tracing the same series of beds westward into the Mississippi valley, they are found to become very much thinner, hardly exceeding one-tenth of the thickness in the mountains. This immense thickness of the component strata is not peculiar to the Appalachians but reappears in the typical mountain ranges everywhere: the Wasatch range has 31,000 feet of strata, the Coast Range 30,000 feet, the Alps 50,000 feet, etc. The thick series of strata which make up a mountain chain are usually conformable throughout; deposition was, for the most part, continuous, and there was little or no loss from denudation, though in some cases the region which subsequently was upheaved into the range had its oscillations of level, recorded now in unconformities. This may be seen, for example, in the Ouachita range of Arkansas.

Another well-nigh universal fact concerning the structure of mountain ranges is the intense folding or plication of their strata, often accompanied by great thrust faults. The degree of plication varies much in different ranges. The Uinta Mountains are formed by a single great and gently swelling arch of strata, faulted along its northern slope. So gentle is the curvature of the beds that in a single view they often seem to be quite horizontal. Much more commonly the strata are thrown into a series of parallel folds, which sometimes are open, upright, and symmetrical, as in the Jura Mountains of Switzerland; its folds are so symmetrical and regular that a section across the parallel ridges looks like a diagram. This comparatively gentle folding is, however, not the rule, but rather an intense compression and plication. The Appalachians are thrown into closed, asymmetrical, and overturned folds, with frequent great thrust faults (see Fig. 93, p. 238). The Sierra Nevada is so intensely plicated that the thickness of its strata has not yet been estimated. The Alps have undergone such enormous compression that many of the ridges are in the form of fan folds (*i.e.* the anticlines are broader at the crest than at the base), while others have been pushed over to an inverted position. The combination of this violent contortion with faults and thrusts often results in an indescribable confusion and chaos of forms, which it is exceedingly difficult to comprehend.

The two main characteristic features of mountain ranges are, then, the immense thickness of the strata of which they are made, and the compression and folding or faulting which they have undergone. Certain minor structures which accompany these more striking features should, however, not be overlooked. In the first place, the folded strata of mountain ranges are very generally cleaved, or fissile, or both, the planes of cleavage or fissility running parallel with the axes of the folds. (2) The major folds are themselves composed of successive series of minor folds in descending order of magnitude, the smallest of them being visible only with the microscope. (3) Dynamic metamorphism is an almost universal feature of mountain ranges, the transformation of the rocks being in proportion to the intensity of the plication. The microscope gives eloquent testimony to the enormous forces which have been at work, by showing how the minerals have been mashed and flattened, rendered plastic and flowing like wax in a hydraulic press. (4) Masses of igneous rocks are very often, though not always, associated with mountain ranges, and many such ranges have a core of igneous rock, often granite, with strata flanking it on both sides.

Origin of Mountain Ranges

The manner in which mountain ranges have been formed must be deduced from a careful study of their structure, for no one has ever witnessed the process of that formation. Mountain building may be going on at the present time; indeed, there is no reason to suppose that it is not, but so slowly is the work carried on that it withdraws itself entirely from observation. Nevertheless the general course of events may be inferred with much confidence from the structure of the range.

The first step in the formation of a mountain range must evidently be the accumulation of an immensely thick body of strata. This, of course, must have taken place under water, and the only body of water large enough is the sea. Furthermore, our studies of modern marine deposits have taught us that thick strata can be accumulated only in rather shallow water and parallel with shorelines. This shoal water origin of their strata is confirmed by the examination of actual mountain ranges, where we find great masses of conglomerates, ripple-marked and sun-cracked sandstones and shales, and abundant other testimony of deposition in shallow water. To accumulate thick strata in shoal water the bottom must subside as the sediments are piled upon it, else the water would be filled up and deposition cease. Such a sinking trough is a geosyncline, and in geosynclines filled with sediments is the cradle of the mountains. The area of the trough varies from time to time, as do also the position of the line of maximum subsidence and the relative rate of depression and sedimentation, so that the depth of water varies. We saw above that the strata of mountain ranges are very much thicker than the same strata in the adjoining plains, which means that the ranges have been formed along the lines of maximum sedimentation.

The second stage in the building of a range is the upheaval of the thick mass of strata into a series of anticlinal and synclinal folds, which may be upright, open, and symmetrical, or closed, asymmetrical, inclined, or inverted. This, as we have already learned, can be produced only by *lateral compression*, a conclusion which is sustained not only by the mechanics of folding and faulting, but also by the less obvious structures, such as cleavage and fissility, metamorphism, the microscopic crumplings and plications, and the crushing and flowage of the mineral particles. Experiments upon the lateral compression of plastic substances under load give the same result. The compressing force does not raise anticlines with great cavities beneath them, for such arches could not well be self-supporting, but mashes together the whole mass of strata, raising them into folds and wrinkles, crowding the beds into a greatly reduced breadth; or when they are not sufficiently loaded to be plastic, breaking and dislocating them in great thrust faults. Certain mountain areas in Pennsylvania have been compressed into one-sixth the breadth originally occupied. It is not necessary to suppose that a mountain range was thrown up by one steady movement. On the contrary, there is good reason to believe that repeated movements, separated it may be by long intervals of time, have been engaged in the work.

That mountain ranges have been forced upward by lateral compression is an unquestioned fact, but to determine how that compression was generated is a much more difficult problem. The most satisfactory explanation yet offered is that the compression is due to the contraction of the globe from cooling. The earth's crust long ago reached a state of fairly constant temperature, but the highly heated interior is steadily cooling by radiation, and contracting. The crust must follow the shrinking interior, and is thereby crowded into a smaller space, which sets up irresistible lateral pressure, to which the crust must give way, even though it were far more rigid than steel. A withered apple has a wrinkled skin because the fruit has shrunk from loss of water, and the skin, crowded into a smaller space, is folded and wrinkled.

Various objections have been urged against the contraction theory, chiefly on the ground that the cause is insufficient to do the work demanded of it. Those objections cannot be completely answered because of our ignorance of the quantitative factors involved in the problem, but the fact remains that no other suggestion explains the facts of mountain structure so well.

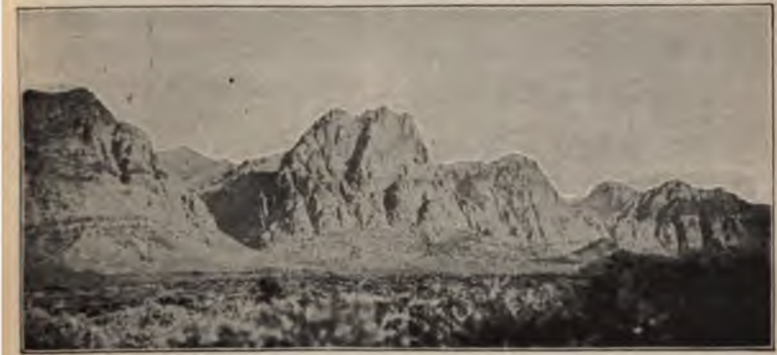

FIG. 136.—The Charleston Mountains, Nevada. One of the Basin Ranges. (Photograph by Merriam.)

There are certain mountain ranges which have an exceptional structure and must have had a correspondingly different mode of origin. In the Great Basin which lies between the Sierra Nevada and the Wasatch Mountains, are a number of parallel mountain ranges with a prevalent north and south trend, which are collectively called the Basin Ranges. These mountains are not folds of very thick strata, but tilted *fault blocks*, which have been made by normal faults, each upthrow side standing as a great escarpment, but with a tilted top that gradually slopes back to the foot of the next block, to which it stands as the *downthrow* side. The processes of denudation have carved these tilted blocks into peaks and ridges of the ordinary kind. The boundary ranges, the Sierra Nevada and the Wasatch, although mountains of folding, have themselves been modified by the same process, for each of these ranges has a great fault along its base, the Great Basin being on the downthrow side with reference to each of them. The fault of the Sierras is on the east side of the range and hades toward the east, that of the Wasatch is on the west side and hades to the west. The dislocations of this region have been kept up till a very recent period; in southeastern Oregon the fault scarps are still very plainly shown, the upthrow sides forming ridges, and the downthrow sides valleys in many of which water has gathered into lakes (see Fig. 104). Near Salt Lake City the movements may even yet be in progress. In Fig. 52 (p. 132) is shown an alluvial cone at the foot of the Wasatch Mountains; on the right side of the cone, near its upper end, may be seen a low fault scarp, which could not have been very long maintained in such incoherent materials. This exceptional mountain structure seen in the Basin Ranges is, then, due to normal faulting.

Another type of mountain structure different from either of those mentioned is the *laccolithic mountain.* A laccolith (see p. 283) is a rounded, intrusive mass of igneous rock which has lifted up an arch of strata above it into a dome, but has not reached the surface to flow out as lava. A laccolithic mountain may stand isolated, like Little Sun Dance Hill (see Fig. 128), or several of them may be grouped together, as in the Henry Mountains of southern Utah, or again, they may form extensive portions of true ranges, as in the Elk Mountains of Colorado.

The **Date of Mountain Ranges** means the geological period in which they were first upheaved above the sea. This date is subsequent to the newest strata which are involved in the movement, and earlier than that of the oldest strata which did not take part in the movement, but must have done so, had they been present. Strata which rest unconformably against the flanks of a range must have been deposited after the folding movement was accomplished. If the newest folded strata and the oldest unmoved strata be of successive geological periods, the date of the upheaval is placed between those two periods and said to close the older one for the particular region involved. The subsequent history of a mountain range after its final upheaval above the sea must be read in its denudation and in the evolution of its topography and drainage.

DENUDATION OF MOUNTAINS

Mountains as we see them are never in the shape which they would present, were the forces of compression and upheaval alone concerned in their formation. Every mountain range has been profoundly affected by the agencies of denudation, and their ridges and peaks, their cliffs and valleys, have been carved out of swelling folds and domes, or angular, tilted fault blocks. As upheaval is a slow process, denudation must have begun its work as soon as the crests of the folds made their appearance above the sea, or above the level of the ground, so that probably no range ever had the full height which the strata, if free from denudation, would have given to it. Upheaval, though sometimes slow enough to allow rivers to keep their channels open, is yet too rapid to be kept in check by the processes of general atmospheric weathering, and so the ranges grew into great uplifts. But as soon as the movement of elevation ceased, denudation began to get the upper hand, for as we have learned, mountains are the scene of exceptionally rapid erosion. The steepness of their sides gives great power to the streams which course down them, they cause the discharge of the atmospheric moisture in rain or snow, they are terribly riven by the frost, and they are frequently cut and gashed by glaciers. For a long period the effect of denudation is to greatly increase the ruggedness of the mountains, carving folds into ridges and cliffs, and ridges into bold and inaccessible peaks, but sooner or later the mountains are worn down lower and lower, and are eventually levelled with the plains from which they spring. In the process of degradation, the synclines often resist wear better than the anticlines, and standing up above the level, form the synclinal mountains of many ancient ranges.

From the geological point of view mountains must be regarded as short-lived and ephemeral; low-lying plains persist for a longer time than do lofty ranges, as rivers may outlast many generations of lakes. Consequently, among the mountain chains of the globe, we everywhere find that the lofty ranges are those of comparatively recent date, while ancient mountains have been worn down into mere stumps. The Appalachians have been reduced nearly to base-level, and their present condition is that of a reëlevated and dissected peneplain, the ridges and valleys of which are determined by the position, attitude, and alternation of harder and softer strata. In its pristine state this very ancient range may well have been as lofty as the Alps or Andes. Of course, there is no mathematical ratio between the youth of a range and its height, for moderately folded strata of moderate thickness never could have formed very high mountains, but in a general way it is true, that very high ranges are youthful, and that very old ranges are low. The process of degradation may go so far as to sweep away a mountain range to its very roots, leaving only the intensely plicated strata of the plain as evidence that mountains ever existed there. Of such a nature is the upland of southern New England and the great metamorphic area of Canada, both of which probably once carried ranges of high mountains.

SUCCESSIVE CYCLES OF DENUDATION.

We have seen that any region, however lofty and rugged, must eventually be worn down to base-level, provided only that the country remain stationary with reference to the sea until the process of degradation is complete. It is doubtful, however, whether any extensive region of hard rocks has ever been absolutely reduced to base-level: the usual result is the formation of a peneplain, a low-lying, featureless surface of gentle slopes and with only occasional eminences rising above the general level. Reëlevation of such a peneplain at once revivifies the streams and gives all the destructive agencies new powers. The peneplain is attacked and carved into valleys and hills, the valleys being rapidly cut down to base-level, while the divides and hills are much more slowly removed. If time enough be granted, the rugged country formed from a dissected peneplain is in its turn worn down to a second peneplain at a lower base-level. This alternate upheaval and wearing down together constitute a *cycle of denudation*, from base-level back to base-level. A complete cycle is one in which the whole region is reduced to a peneplain before the reëlevation occurs, and a partial or incomplete cycle is one which is interrupted by upheaval before the region is cut down, and only small and local peneplains have been formed. From a study of an old region several cycles of denudation may frequently be made out, represented by the remnants of dissected peneplains at different levels preserved in the harder rocks. The successive adjustments of the drainage system are a valuable auxiliary in working out the history of the cycles.

As an excellent example of these cycles of denudation whose marks are preserved in the structure of the rocks, we may take the Appalachian Mountains, which have been studied with great care. The cycles have been worked out elaborately, but only an outline of the more striking events can be given here.

These mountains began as a great geosyncline in which throughout the vast lengths of the Palæozoic era (see p. 365) were accumulated enormously thick masses of shoal water sediments. At the close of that era a number of crustal movements set in, crushing the sides of the geosynclinal trough, and crumpling the mass of strata contained in it into a series of roughly parallel, closed, inclined, or overturned folds, forming doubtless a very lofty range of mountains. During the long ages of the Mesozoic era (see p. 441) the mountains were attacked and worn down by the destructive agencies; and by the time the Cretaceous period was reached (see p. 474) the range had been reduced to a peneplain, with only a few hills rising above its almost featureless level, — hills which are now the peaks of western North Carolina, the highest points of the range at present.

The present height of these peaks is due to subsequent reëlevation. This plain is called the Kittatinny peneplain, because the ridge of that name in Pennsylvania and New Jersey is one of the remnants of it. To the observer who can overlook the billowy ridges of the present range their even sky line is very striking, and these ridges are all composed of the hardest rocks, which all rise to nearly the same level. To reproduce the plain it would be necessary to fill the valleys between the Blue Ridge on the east and the plateau on the west up to the level attained by the hard ridges, and this would give a gently arched surface, sloping very gradually to the Mississippi valley and the Atlantic. On this peneplain were already established the great streams which flow to the ocean, such as the Susquehanna and the Potomac.

Next the peneplain was raised very gradually to a height of 1400 feet in Virginia, diminishing in both directions from this point, and the denuding forces once more attacked and dissected the plain, the larger streams holding their transverse courses and sawing through the hard strata, which were left standing as ridges by the cutting of the longitudinal valleys along the more destructible beds. Denudation had cut down the softer beds to one general level, called the Shenandoah peneplain, the period of rest being long enough to bring all the areas of soft and soluble beds to this level, but not to materially lower the ridges of the more resistant strata.

"The swelling of the Appalachian dome began again. It rose 200 feet in New Jersey, 600 feet in Pennsylvania, 1700 feet in southern Virginia, and thence southward sloped to the Gulf of Mexico. . . . In consequence of the renewed elevation, the streams were revived. Once more falling swiftly, they have sawed, and are sawing, their channels down, and are preparing for the development of a future base-level." (Willis.)

This example is sufficient to show the value of the physiographic method to the geologist in supplementing the knowledge derived from the study of sedimentation.

PART IV

HISTORICAL GEOLOGY

CHAPTER XX

FOSSILS

A FOSSIL is the impression or remains of an animal or plant which has been entombed in the rocks by natural causes.

A knowledge of fossils is indispensable to the geologist because they give him the means of establishing a consecutive chronology of the earth, and teach him much concerning the changes of land and sea, of climate, and of the distribution of living things upon the globe. To comprehend the lessons taught by fossils, it is essential not only that the student should familiarize himself with actual specimens, but also that he should have some acquaintance with the elements of zoölogy and botany, else he cannot appreciate the distinctions which obtain between the fossils of widely separated periods of time.

I. HOW FOSSILS WERE EMBEDDED IN THE ROCKS

The conditions of the preservation of fossils are much more favourable to some kinds of organisms than to others. It is only under the rarest circumstances that soft, gelatinous animals, which (like jelly-fish) have no hard parts, can leave traces in the rocks. The vast majority of fossilized animals are those which have hard shells, scales, teeth, or bones; and of plants, those which contain a sufficient amount of woody tissue.

Again, the conditions under which organisms live have a great influence upon the chances of their preservation as fossils. Land animals and plants are much less favourably situated than are aquatic forms, and since by far the greater number of sedimentary rocks were laid down in the sea, marine organisms are much more common as fossils than are those of fresh water.

Few rocks, and those unimportant, are accumulated on land, and so fossils are rarely preserved on land surfaces, though they are occasionally buried in blown sand or in the soil. Peat bogs are, however, excellent places for fossilization, and the coal seams have yielded great numbers of fossils, principally of plants. The remains of land animals and plants, especially of the latter, are sometimes swept out to sea, sink to the bottom, and are there covered up and preserved in the deposits; but such occurrences are relatively uncommon. Lakes offer much more favourable conditions for the preservation of terrestrial organisms. Surrounding trees drop their leaves, flowers, and fruit upon the flats and shallows of fine mud, insects fall into the quiet waters, while quadrupeds are mired in mud or quicksand and soon buried out of sight. Flooded streams bring in quantities of vegetable débris, together with the carcases of land animals, drowned by the sudden rise of the flood. When the carcase of a freshly drowned mammal is washed into the lake, it immedidiately sinks to the bottom; and if sufficient sediment be deposited upon it, it will be held there and fossilized as a complete skeleton. But if little sediment be thrown down upon it, the carcase will rise and float, when the body is distended by the gases of decomposition. Floating thus, it will be pulled about by the flesh-eating creatures which inhabit the lake, dropping one bone here and another there, over a wide area.

The great series of lake deposits, which for long ages were formed in various parts of our West, have proved to be a marvellous museum of the land and fresh-water life of that region. On the fine-grained shales are preserved innumerable insects and fishes, with multitudes of leaves, many fruits and occasionally flowers, while in the sands and clays are entombed the bones of the reptiles, mammals, and, more rarely, birds of the land, mingled with those of the crocodiles, turtles, and fishes that lived in the water. Similar lake-beds are known in other continents.

It is on the sea-bed that the conditions are most favourable to the preservation of the greatest number and variety of fossils. Among the littoral deposits ground by the ceaseless action of the surf, fossils are not likely to be abundant or well preserved, but in quieter and deeper waters vast numbers of dead shells and the like accumulate and are buried in sediments. The fossils are not, however, uniformly distributed over the sea-bottom; in some places they are crowded together in multitudes, while large areas will be almost devoid of them. The differences are due to variations in temperature, in the character of the bottom, in food supply, and other conditions. In tropical seas, swept by currents which bring in abundant supplies of food, the luxuriance of life is wonderful, and in such places a correspondingly large number of fossils are preserved. However, even under the most favourable circumstances, the fossils can never represent more than a fraction of the life of their times. Indeed, the wonder is that so much of the life systems of past ages has been preserved, rather than that so large a part has been irretrievably lost.

The ways in which fossils are preserved vary much, according to circumstances, but three groups include all the principal kinds.

(1) Preservation of more or less of the original substance. In certain rare instances an organism may be preserved intact, as have been the carcases of the extinct species of elephant and rhinoceros which are found in the frozen gravels of Siberia, which after thousands of years of burial are still eagerly devoured by the wolves. Much more common is the decomposition of the soft structures and the preservation of the hard parts,—bones, shells, etc. Most of the shells and bones found in the rocks of later geological date are composed of the material originally belonging to them, though they have suffered much loss of substance. The carbon of coal plants is that which was present in the living vegetation, but the volatile matters have disappeared.

(2) Entire loss of substance and retention of form. In this class of fossils all the original material of the organism has been lost, and no trace of its internal structure is retained, but only the external form has been reproduced in some different material. Under this class we may distinguish two principal varieties: (*a*) *Moulds* and (*b*) *Casts*. A *mould* is formed when the fossil is embedded in sediments, which accurately reproduce its external form, and harden so as not to collapse when the fossil is removed. Percolating waters then dissolve away the organism entirely, leaving only a cavity, which is the mould. It is often possible to reproduce the form of a vanished fossil by filling the natural mould with plaster of Paris, gutta-percha, or similar substance. Impressions of footprints, which may be placed in the same category as moulds, have already been explained (see p. 227).

Casts are formed when the mould is filled by some solid substance deposited from percolating waters, thus reproducing the form of the fossil, as is done artificially with plaster or gutta-percha. If the fossil were hollow, like a shell, we frequently find a combination of internal cast with an external mould in the same specimen. At the time the fossil is embedded its interior is filled with the same sediment, which hardens and forms an internal cast, exactly reproducing the form of the interior. The shell itself is then dissolved away, leaving a space between the outer mould and the inner cast. Moulds and casts are commonest in rocks which permit percolating waters to traverse them freely, such as sandstones and coarse-grained limestones. An interesting form of cast is the *brain-cast*, which is made by the fine-grained sediment which fills the cranial cavity of an embedded skull, often reproducing the form of the brain with much accuracy.

(3) Loss of substance with reproduction of form and structure. Fossils of this class are also called petrifactions and pseudomorphs (the latter a term borrowed from mineralogy). Here the original material of the organism has been more or less completely removed, and other material substituted for it; but the substitution has been so gradual, molecule by molecule, that not only the external form but also the microscopic structure has been perfectly reproduced.

Several scantily soluble substances act as petrifying materials, the most perfect results being given by silica. A silicified bone, or tooth, or bit of wood, differs from the original only in weight, colour, and hardness, and when a thin section is examined under the microscope, the minutest details of structure may be made out as perfectly as from the unaltered original. $CaCO_3$ is a very common petrifying agent, but it often obliterates structure by crystallizing after deposition; less usual are iron pyrites and siderite. It need scarcely be said that only hard substances — wood, bones, shells, etc. — are sufficiently durable to be preserved in this way, though a petrifaction of soft tissues has been reported as occurring under very exceptional circumstances.

II. WHAT MAY BE LEARNED FROM FOSSILS

The principal value which fossils possess for the geologist lies in the assistance which they give him in reconstructing the history of the globe. This they do in several ways.

(1) **In determining Geological Chronology.** — The most obvious way in which to make out the relative ages of a series of stratified rocks is to determine their order of superposition, for the oldest will be at the bottom and the newest at the top (see p. 221). But this method is of only local application and will not carry us far in an endeavour to compile a history of the whole earth. It cannot enable us to compare even the rocks of different parts of the same continent, for any exposed section is but a small fraction of the whole series of strata. More embarrassing still, strata change their character from point to point, limestone being laid down in one place while sandstone is accumulating in another. Still less can the order of superposition help to determine the relative ages of rocks in different continents, for this order in North America can be no guide to the succession in Africa or Australia. This conclusion does not imply that order of superposition may be safely neglected; on the contrary, it is an indispensable aid, but it must be studied in connection with the fossils.

Since the first introduction of life on the globe it has gone on advancing, diversifying, and continually rising to higher and higher planes. We need not stop to inquire how this progression has been effected; for our present purpose it is sufficient to know that progress and change have been unceasing and gradual, though not necessarily occurring at a uniform rate. Accepting, then, the undoubted fact of the universal change in the character of the organic beings which have successively lived on the earth, it follows that rocks which have been formed in widely separated periods of time will contain markedly different fossils, while those which were laid down more or less contemporaneously will have similar fossils. This principle enables us to compare and correlate rocks from all the continents and, in a general way, to arrange the great events of the earth's history in chronological order.

The general principle that similarity of fossils indicates the approximate contemporaneity of the rocks in which they are found, must not be taken too literally, for it is subject to certain limitations and exceptions.

(*a*) Exact contemporaneity is not meant, for the progress of life is very slow, and rocks formed thousands of years apart may yet contain precisely similar fossils.

(*b*) Animals and plants differ in different parts of the world, so that contemporaneous rocks formed in widely separated regions will always show a certain amount of difference in their contained fossils. In comparing the rocks of two continents, it is often exceedingly difficult to decide just how much of a given difference in the fossils is to be ascribed to a difference in the time of rock formation, and how much to mere geographical separation.

(*c*) New forms of animals and plants originate in some particular area and spread in all directions from that area, until stopped by some obstacle of climate or topography which they cannot surmount. The diffusion of new forms often occasions the extinction of old ones which were not so well fitted to survive. These processes take time, and a group of organisms may make its appearance in one part of the world long before it spreads to another, while ancient types may linger in certain localities long after they have elsewhere become extinct.

Despite these limitations we find that, speaking broadly, the order of succession in the appearance and extinction of the great groups of fossils is much the same for all parts of the earth, and we may confidently assume that the grander divisions of geological time are of world-wide significance.

It will now be easy to understand why the fossils in two groups of unconformable strata are generally so radically different. It is because of the long lapse of unrecorded time at that point, during which organic progress continued; when deposition was resumed, the animals and plants were all new, and so the change is abrupt. If one is reading a book from which a dozen chapters have been torn out, the change of subject will appear violently abrupt; to bridge over the gap one must find another copy of the book. Likewise, to fill up the gap of a great unconformity, we must go to some region where deposition went on uninterruptedly, and there we may trace the gradual and steady change in the fossils.

A geological chronology is constructed by carefully determining, first of all, the order of superposition of the stratified rocks, and next by learning the fossils characteristic of each group of strata. The history is recorded partly in the nature and structure of the rocks, partly in the fossils, and partly in the topographical forms of the land and the courses of the streams. By combining these different lines of evidence, local histories are constructed for each region, until from these the story of the whole continent may be compiled. The comparative study of the fossils then gives the clue for uniting the history of the different continents into the history of the earth. Much remains to be done before this great task can be accomplished, but already we have an outline of the scheme which future investigations may fill up.

It necessarily follows from the way in which sedimentary rocks are formed, and the local nature of upheavals and depressions of land, that in no single locality can the entire series of strata be observed, and that each region can display but a certain proportion of the whole record. The different parts of our continent are of vastly different geological dates, and even the same area may have been many times a land surface, and as often a sea-bottom. Unconformities, more or less wide-spread, offer a natural and convenient mode of dividing the strata into groups, but the difficulty with this method is that the dates of elevation and depression so seldom correspond in different regions, that divisions thus made are apt to be of more or less local validity. The only standard yet devised which is applicable to all the world is that founded upon the progress of life.

The comparison between human history and geological history is one that has very often been made, but trite and hackneyed as it is, it is none the less instructive. The history of civilized nations is the record of continuous development, not without retrogressions and periods of comparative stagnation, but having no actual gaps in it. For the sake of convenience, history is divided into certain periods in accordance with the predominance of certain great ideas and principles, and these periods are real, representing the salient facts in the progress of development. Each period is, however, but the outcome of the antecedent periods, and the ideas and principles which characterize it were slowly maturing, it may be through centuries, and even after other ideas have risen to predominance, older ones continue to live and influence the world. For example, when we speak of the age of the French Revolution, we refer to a time when a certain set of political ideas and principles were the most striking and influential factors in the development of the civilized world, beginning with the visible changes of 1789 and ending with the restoration of the Bourbons in 1815. But the tremendous outbreak was slowly preparing throughout the Eighteenth Century; the conflagration was proportionate to the materials that had been gathered for it. Nor, on the other hand, could the effects of the great movement be undone by the return of the exiled king. To this day the whole civilized world feels the effects of the convulsion, and the entire course of the Nineteenth Century would have been different but for the French Revolution.

Historians are careful to distinguish between events and the record of them. Events are continuous and bound up into a chain of consequences, every one of which is dependent upon others, while the records may be scanty, interrupted, confused, unintelligible, even misleading and falsified, so that it is no easy task to write history accurately and without attributing undue importance to this or that principle or policy.

These considerations fully apply to geological history; its divisions are founded upon the rise and culmination of great groups of animals and plants, which one after another have risen to predominance and then declined, their place being taken by others better fitted for the new conditions. These successive culminations are not sudden, but gradual and continuous, and the beginnings of each group are to be found in time long before the period of its predominance. Nor is decline immediately followed by extinction; one group slowly gives way to another, but long after the first has ceased to be the principal fact in the world's life, it may linger on in diminished importance until, perhaps, it finally disappears. The geological periods, therefore, like historical periods, had not definite beginnings and endings, for one slowly fades into another, but they are none the less actual because the lines of separation between them must often be somewhat arbitrarily drawn, and they cannot always be made to correspond in different regions.

In geology, as in history, we must distinguish between the events and the records of them. The more complete the records, the more obviously continuous and gradual was the course of events; only imperfect records can make the history seem broken and disjointed. As our science was first developed in western Europe, where the great groups of strata are mostly separated by unconformities, with abrupt changes in the fossils, the older geologists very naturally concluded that the great divisions of geological time were marked by frightful catastrophes which devastated the earth, destroying every living thing upon it. Each group of rocks was looked upon as the product of a long and tranquil period, and its fossils were believed to represent an entirely new creation. Though opposed by some far-seeing minds, the doctrine of *Catastrophism*, as it was called, long held sway, but was shown to be erroneous, when the study of geology was carried to other parts of the world.

Then it appeared that the supposed catastrophes, if they occurred at all, were not general, but local, that records missing in Europe had been preserved, partially at least, in other continents. Enough of these missing records has been recovered to show that the earth's progress was not by a series of abrupt and sudden changes, but by a continuous, orderly development.

Major divisions of *geological time* are founded upon the more striking changes in the animals and plants, while for minor divisions the more detailed differences in the organisms are employed. Parallel with the divisions of *time* run the groups or systems of the *strata*, for characterizing which both the physical nature and structure of the rocks and the fossils are employed. In the very difficult and complicated task of compiling the earth's history, no kind of evidence can be ignored, and wide knowledge and sound judgment are needed in the work, so that no particular class of records shall be either over- or under-valued.

Though the goal of geological inquiries is to construct the history of the earth as a unit, this goal can only be reached by the minute and exhaustive study of the local histories. Each of the latter has certain peculiarities of its own which must be determined, and hence arises the multiplicity of local names for groups of strata, so confusing to the student. Local names are useful, because they avoid the necessity of premature comparisons and correlations, which may lead to the direst mistakes.

(2) **As Evidence of Geographical Changes.** — We have seen that from the composition and structure of the stratified rocks themselves much may be learned concerning the geographical conditions under which they were formed, and of the subsequent geographical changes of the region in which they occur. Fossils supplement this information regarding the body of water in which the rocks were laid down, whether fresh or salt, deep or shallow, near or far from land, in an open sea or a closed basin, and whether such a closed basin had occasional or constant communication with the ocean. The stratified rocks which now form part of the land surface give us information only concerning the former extension of bodies of water over what is now the land, but they can

tell us nothing of the land areas which have disappeared beneath the sea. In this connection fossils are of great assistance, for, in certain instances, the distribution of marine fossils points to the presence of land barriers to migration which no longer exist, while the fossils of land animals may demonstrate the former existence of land bridges between regions which have long been separated by water. Thus it may be shown that North America was frequently and for long periods of time connected with Asia across Bering's Sea, and that its union with South America is of geologically late date.

(3) **As Evidence of Climatic Changes.** — The remarkable climatic changes through which various parts of the earth have passed are indicated by fossils. Indeed, with the exception of glacial marks, and ice-formed deposits, fossils offer almost the only trustworthy evidence available as to these changes of climate. Thus, when we find in the rocks of Greenland the remains of extensive forests of such trees as now grow in temperate latitudes, the only possible inference is that Greenland now has a far colder climate than when those forests existed. The same conclusion follows from the presence in the rocks of Wyoming and Idaho of great palm leaves and other subtropical plants associated with the bones of crocodiles and other reptiles, such as live only in warm regions. In deposits of a far later date occur bones of the reindeer in southern New England and in the south of France, walrus bones in the sands of New Jersey, and those of the musk-ox in Arkansas; all of which shows that at one time these regions had a far colder climate than at present.

The evidence as to climatic changes which is presented by fossils must, however, be treated with great caution, because even nearly allied species often have entirely different habits and flourish in quite different climates. Most fossils belong to extinct species, as to whose climatic relations we have no knowledge. Before any conclusion concerning changes of climate can be regarded as established, we should have the testimony of species still living, or, if that is not possible, the evidence must be drawn from large assemblages of different kinds of animals and plants.

Such an extreme case as the fossil plants of Greenland is sufficient evidence without further corroboration.

III. CLASSIFICATION OF GEOLOGICAL TIME

The method of making the divisions and subdivisions of geological time is not yet a fixed one, and there is much difference in the usage of various writers. The names of the divisions also have been given at various times and in many lands, according to no particular system. Most of these names have been taken from the locality or district where the rocks in question were first studied; as Devonian from Devonshire, Jurassic from the Jura Mountains. Some are named from a characteristic or prevalent kind of rock, such as Cretaceous (Latin *creta*, chalk) and Carboniferous. Of late there has been a tendency toward a more uniform method of nomenclature, and to the use of one set of terms for the divisions of time, and another and corresponding set for the divisions of the strata. The grander divisions of time are called eras, and in descending order we have periods, epochs, and ages. The following table represents the divisions in the scale of time and the scale of rocks which have been adopted by the International Geological Congress.

TIME SCALE	ROCK SCALE
Era	Group
Period	System
Epoch	Series
Age	Stage
	Substage
	Zone

It will be observed that the subdivision is carried further in the scale of rocks than in that of time, because of the generally local character of these minor subdivisions. The names employed are, as yet, the same for both scales, and we speak of the Palæozoic Era or Group, and of the Silurian Period or System. It has been proposed to give separate names to the divisions of the two scales, d this would be an improvement in some respects, but the pro-sal has not been carried out.

TABLE OF GEOLOGICAL DIVISIONS

Cenozoic Era	Quaternary Period or Pleistocene Epoch	
	Tertiary "	Pliocene Epoch
		Miocene "
		Oligocene "
		Eocene "
Mesozoic Era	Cretaceous Period[1]	
	Jurassic "	
	Triassic "	
Palæozoic Era	Permian Period	
	Carboniferous "	Upper Carbonif. Epoch
		Lower Carbonif. "
	Devonian "	Chemung "
		Hamilton "
		Corniferous "
		Oriskany "
	Silurian "	Lower Helderberg "
		Onondaga "
		Niagara "
	Ordovician "	Canadian "
		Trenton "
	Cambrian "	Potsdam "
		Acadian "
		Georgian "
Eozoic Era	Algonkian Period	
Azoic Era	Archæan Period	

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[1] The subdivisions of the Mesozoic Periods are so different for different parts of continent that they are omitted in the table.

CHAPTER XXI

ORIGINAL CONDITION OF THE EARTH—PRE-CAMBRIAN PERIODS

As we trace the history of mankind back to very ancient times, we find that the records become more and more scanty and less intelligible, until history fades into myth and tradition. Of a still earlier age we have not even a tradition; it is *prehistoric.* Similarly, among the geological records the earliest are in a state of such excessive confusion that they are exceedingly difficult to understand, and between different observers there are radical differences of opinion both as to the facts and as to their interpretation. Furthermore, there must have been an inconceivably long time earlier than the most ancient recorded periods, as to which conjecture and inference are the only resource. In these difficult straits astronomy offers valuable assistance to the baffled geologist. The *Nebular Hypothesis* is a scheme of the development of the solar system, which, though not yet demonstrated, nor free from difficulties, so well explains the known facts that it is almost universally accepted as essentially true.

According to this hypothesis the place of the present solar system was originally occupied by a vast rotating nebula, a mass of intensely heated vapour, or possibly clouds of meteorites, extending beyond the orbit of the outermost planet. As the nebula cooled by radiation, it contracted, leaving behind it successive rings, like those of the planet Saturn, but on a vastly larger scale. The rings kept up the rotation imparted by the nebula, and all of them lay in nearly the same plane. Unequal contraction in various parts of each revolving ring caused it to break up and gather by mutual attraction into masses. If these rings were composed of relatively small solid masses, like meteorites, or if they had solidified by condensation of the vapours, the heat generated by the collisions, as the broken ring was gathered into a mass, would suffice to raise the temperature and liquefy or vapourize the mass. By revolution the nebulous masses would assume a spheroidal shape and become planets. The central mass of the original nucleus forms the sun, which is still in an intensely heated, incandescent state.

This is not the place to discuss the evidence for an astronomical speculation, but we may regard it as in the highest degree probable that when our earth first began its separate existence, it did so as a globe of fused or even vaporous material, in which the various substances arranged themselves very much in the order of their density. This conclusion is much strengthened by the character of the globe itself. The specific gravity of the earth as a whole somewhat exceeds 5, while that of the rocks on the surface ranges from 2.5 to 3, which shows that the interior of the earth is much denser than its outer portion. We have already learned that the earth's interior is still highly heated, and its shape, that of an oblate spheroid flattened at the poles, is that which would be assumed by a rotating liquid or plastic body.

For long ages the earth must have continued as a glowing star, its "*astral period*," but gradually an outer crust was formed by the slow cooling of the surface. How often this thin crust was broken up and remelted and formed again, we have no means of knowing, but eventually a solid, permanent crust was established and thickened by additions from below, until, by the combined effects of cooling and enormous pressures, the globe has reached its present condition, whatever that may be (see p. 32). Even after a solid crust had been formed, it must have long remained so hot that no water could condense upon its surface. All the water of the oceans must then have been in the atmosphere, increasing many fold the weight of the latter and the pressure which it exerted upon the earth's surface. Owing to this great pressure the first condensation of steam must have occurred at temperatures far above the boiling-point of water for the present atmospheric pressure (212° F.). Superheated water is an agency of extreme power in destroying and recombining materials, and the earliest boiling oceans must have set up very vigorous chemical work upon the heated crust. In the course of ages the surface of the globe became so far cooled and the crust so thick that the earth's interior heat ceased to control the temperature of its surface.

THE PRE-CAMBRIAN PERIODS — I. ARCHÆAN

It is unfortunate that an account of historical geology should necessarily begin with the most difficult and obscure part of the whole subject, but the treatment must be in accordance with the chronological order, and the oldest rocks are the least intelligible. The ordinary criteria of the historical method, namely, the stratigraphical succession and the comparison of fossils, fail us here almost entirely, and the only way of correlating the rocks of different regions and continents is by means of the characters of the rocks themselves. In the present state of knowledge, "lithological similarity" is not a safe guide. So many metamorphic rocks, once referred to the Archæan, have proved to be of much later date, that some cautious geologists, who have no confidence in "lithological similarities," prefer not to use the term *Archæan* at all, but to employ local terms for the oldest crystalline rocks exposed in a given district.

The Archæan includes the most ancient rocks, often spoken of as the "basement, or basal complex." Its antiquity is best assured in regions where it is separated by thick series of sedimentary or metamorphic rocks from the Lower Cambrian, which can be certainly identified by its fossils. In such regions the Archæan is composed of completely crystalline rocks of various types confusedly mixed together, massive rocks, such as granite and basic eruptives, and foliated rocks, like gneissoid granite, gneiss, and various schists, are intermingled in the most intricate way. Some of these rocks cut the others in the form of dikes and are manifestly of very different dates of formation. The dike rocks may be either massive or schistose. The component minerals are principally orthoclase and acid plagioclase, quartz, hornblende, and mica, with other minerals as accessories. The particles show plainly the intense dynamic metamorphism to which they have been subjected, in their extremely complex arrangement and in their laminated and crushed condition. The Archæan, as thus defined, contains no sandstone, conglomerate, limestone, or any other rock of undoubted sedimentary origin, nor any considerable mass of quartz schist, marble, or graphite schist. The rocks thus referred to the Archæan are not necessarily all of the same age, but they are all of vast antiquity and older than any other known series. They are of very great but unknown thickness, for the bottom of them is nowhere to be seen, and even when thrown up into mountain ranges, erosion has in no case cut so deeply into these rocks as to expose anything different below them.

The reason for uniting these rocks into one group is not merely their likeness in composition, which is not a sufficient criterion, but because of their unique and uniformly complex structure, their resemblance to one another and difference from any other group of rocks, and their invariably fundamental position.

The Distribution of the Archæan Rocks can at present be stated only with much reserve, for they often grade into crystalline schists of demonstrably later date, and much that once was referred to the Archæan is now known to be far more recent. To accurately determine the distribution of the basal complex will require the most extensive, minute, and laborious investigation. The northern part of North America, from the Arctic Ocean to the Great Lakes, is made up of an immense area of schistose rocks, estimated at more than 2,000,000 square miles in extent. Over this vast region occur numerous areas of Archæan rocks, but it is not yet possible to say how much of it belongs in that group and how much is newer.

Beside this principal region are several other minor ones. A narrow band of schistose rocks extends, with some interruptions, from Vermont to Georgia, with shorter parallel belts in eastern Canada and New England. Another great axis is on the site of the Rocky Mountain chain, with several shorter and generally parallel belts from Mexico to Alaska. Isolated areas occur in Missouri, central Texas, New Mexico, and Arizona. In all of these regions are found rocks like the typical Archæan, which stand in the same relation to the newer groups, but how much should be referred to these newer groups is still a question.

In the other continents occur great areas of very ancient gneisses and crystalline schists, but even less than in North America has the distinction been made between the fundamental complex and newer groups. In the following statements no attempt is made to determine how much of the areas mentioned is properly Archæan.

In Europe the principal area lies to the north, covering parts of Ireland and the Highlands of Scotland, with which was probably once connected the great continuous mass of Scandinavia, Finland, and Lapland. Considerable areas also occur in central and southern Europe, as the central plateau of France, parts of Germany and Bohemia, and long, narrow belts in the Pyrenees, Alps, and Balkans. In Asia these ancient crystalline rocks are found in the great mountain ranges, such as the Himalayas, Altai, etc. They make up a large part of the Indian peninsula, and are extensively displayed in China, Japan, and the islands of the Malay Archipelago. The vast central plateau which occupies so much of Africa is principally composed of these rocks, which are also largely exposed in Australia. In South America similar rocks appear in the highlands of Brazil and in the Andes.

Origin of the Archæan Rocks. — This is a problem which has given rise to a great deal of discussion and is still far from solution. One reason for the great differences of opinion is the varying extension which has been given to the term *Archæan*, one writer including rocks which another excludes. The principal suggestions which have been offered are the following: —

(1) That the Archæan rocks are entirely of igneous origin and represent part of the original crust of the earth, added to from below by solidification and cut by many subsequent igneous intrusions. On this view these rocks are far older than any sedimentaries whatever.

(2) That the Archæan rocks were precipitated from solution in the hot seas which first condensed, under great atmospheric pressures, upon the highly heated crust.

(3) That these rocks are intrusive igneous masses, newer than certain strata which rest upon them.

(4) That they were formed by the metamorphism of sedimentary rocks, the massive kinds representing, in large part, the extreme stage of metamorphism by which the sediments were actually melted. Others of the massive kind are igneous intrusions of all subsequent dates.

While we have, as yet, no means of definitely deciding among these conflicting opinions, yet the present trend of investigation seems to be distinctly in favour of the first view, or some modification of it. Certain it is that, if the original crust of the earth be anywhere preserved, it is in the Archæan rocks. As these have been subjected to all the folding and crushing which the earth's crust has undergone, it is not surprising that they should have acquired such a complex and intricate structure and have been so radically metamorphosed. It is hardly necessary to say that the Archæan, as here limited, has yielded no evidence of life, all of those evidences which are generally spoken of as found in the Archæan being of later date, but this negative testimony is of no great value. If these rocks be actually transformed sediments, the profound metamorphism which they have undergone would have thoroughly destroyed any traces of fossils that they might have originally contained. We cannot tell when life was first introduced upon the earth, but we may be very confident that no living thing could have existed when the surface of the crust was glowing hot, or in the oceans boiling even under the enormous atmospheric pressures which accompanied their first condensation.

II. ALGONKIAN

This is the name recently proposed by the United States Geological Survey for the great series of sedimentary and metamorphic rocks which lie between the basal Archæan complex and the oldest Palæozoic strata. While it is possible, though not very likely, that more advanced knowledge may lead us to distribute these rocks partly into the Archæan and partly into the Palæozoic, yet for the present, at least, it is better to form a separate grand division for them.

The Algonkian rocks, which are widely distributed in North America, form an immensely thick mass of strata and of metamorphic rocks which are believed to represent the strata. These metamorphic rocks have hitherto been generally referred to an upper division of the Archæan, called the ***Huronian***, but, so far as can be learned, they occupy the same stratigraphical position as certain little changed sediments, between the fundamental complex below and the Cambrian above. At the base of the magnificent section exposed in the Grand Cañon of the Colorado is a very thick mass of strata, separated by great unconformities from the Archæan gneiss below and from the overlying Upper Cambrian. This mass is again subdivided by minor unconformities into three series. The lower series, at least 1000 feet thick and perhaps more, is made up of stratified quartzites and semi-crystalline schists, cut by intrusive granite. Above this come nearly 7000 feet of sandstones, with included lava sheets, and at the top more than 5000 feet of shales and limestones, in which a few fossils have been found. The two upper series are not at all metamorphic. All these strata are steeply inclined, and upon their edges rests the Upper Cambrian.

A very similar succession of rocks of vast thickness is found in the Lake Superior region, intervening between the Archæan complex and the Upper Cambrian, from both of which they are separated by great unconformities. As in the Grand Cañon section, these rocks are divisible into three series by minor unconformities. The lowest, with a maximum thickness probably exceeding 5000 feet, is much crumpled, metamorphosed, and semi-crystalline. It comprises limestones, quartzites, mica schists, etc., cut by igneous dikes, also much volcanic tuff and agglomerate. Next follows a series of 12,000 feet of less intensely folded but still metamorphic rocks, quartzites, shales, slates, mica schists, with dikes and interbedded sheets of diorite. A few fossils have been found in the quartzites of this series. The third series has a maximum thickness of 50,000 feet, though usually much less.

The lower part of this series is formed by thick lava sheets, interbedded with sandstone and conglomerate, and above is a mass of sedimentary rocks largely derived from the volcanic materials.

Over the great Archæan area of Canada occur many districts of metamorphic rocks which are plainly of sedimentary origin, such as crystalline limestones, schistose conglomerates, as well as volcanic tuffs and agglomerates. In this region and in New England the Algonkian metamorphics apparently grade into the Archæan complex without unconformity. This apparent conformity may, however, very well be due to subsequent dynamic metamorphism, which, as has been proved, may obliterate nearly all traces of a great unconformity. Through the Rocky Mountain region and the Pacific coast mountains, the Archæan is in very many places overlaid by great thicknesses of metamorphic Algonkian rocks, such as quartzites, sandstones, and schists, which are sometimes as much as 12,000 feet thick, as in the Wasatch and Uinta mountains. Other isolated areas are found, as in the Black Hills, where a great mass of schists, slates, and quartzites is separated by a very marked unconformity from the overlying Cambrian; also in Missouri and Texas. The Algonkian rocks of the West have not been subjected to such extreme folding as have those of the East, and hence their distinctness from the Archæan is more clearly marked.

In other continents the distinction has hardly been drawn yet between the Archæan and the Algonkian. In Great Britain, however, are found very interesting parallels with the Algonkian of this country. In Scotland the Torridon sandstones, 8000 to 10,000 feet thick, which are nearly horizontal and almost unchanged, lie unconformably between the oldest Cambrian and the basal Archæan; and in other areas, metamorphic rocks of sedimentary origin occupy a similar position. Many of the crystalline schists of the European pre-Cambrian areas appear to correspond in character and position to the metamorphic Algonkian.

Life in the Algonkian. — In the Grand Cañon and the Lake Superior region determinable fossils have been found in the less changed sediments, but they are too few and scanty to tell us much of the life of the times. It must also be remembered that the rocks in which they occur may eventually prove to be Cambrian. Evidences of life are not wanting in the metamorphic rocks of the eastern and northern regions, but they are indirect and not entirely conclusive. The strata of crystallized limestone are indications of the presence of animal life in the Algonkian seas, for the only way in which such masses of limestone can be formed now is by the organic agencies (see Chapter IX). The great quantities of graphite diffused through many of the schists and the beds of iron ore likewise tend to show the existence of plants at the same time. These indications do not amount to a proof of the presence of life, for it is possible that the limestone, graphite, and iron accumulations were made by chemical processes. Radiolaria have been reported from some of the pre-Cambrian schists of France (this has lately been questioned).

The pre-Cambrian crystalline rocks are remarkable for their wealth of valuable minerals. Immense accumulations of iron ore, in beds from 100 to 400 feet thick, occur in Canada, New York, New Jersey, along the Appalachians from Virginia to Georgia, in Michigan, the Lake Superior region, Missouri, and the Southwest. The great copper mines of Lake Superior are in igneous dikes which intersect sandstones referred to the Algonkian.

It will be obvious to the student how very little is really known regarding the most ancient rocks of the earth's crust. They are enormously thick metamorphic masses of vast geographical extent. In all the continents they form the foundation upon which the oldest fossiliferous sediments were laid down, and, in brief, they are the oldest, the thickest, the most widely distributed and the most important of all the accessible constituents of the earth's crust. Their uniform character, wherever found, the extreme plication and metamorphism which they have undergone, and their world-wide distribution, are all extremely remarkable features, such as recur in rocks of no other age. The Algonkian sedimentary and metamorphic rocks seem to represent the first series of deposits made under water and the earliest chapters in the history of life. The pre-Cambrian rocks indicate that vast periods of time had elapsed before the clearly recorded part of the earth's history began, a time probably longer than all subsequent periods taken together.

CHAPTER XXII

THE PALÆOZOIC PERIODS — CAMBRIAN

THE Palæozoic is the oldest of the three main groups into which the normal fossiliferous strata are divided; it forms the first legible volume of the earth's history, and in interpreting it speculation and hypothesis play a much less prominent part than in the pre-Cambrian volume. The Palæozoic rocks are conglomerates, sandstones, shales, and limestones, with quite extensive areas of metamorphic rocks, and associated igneous masses, both volcanic and plutonic. The thickness of these rocks is very great, estimated in Europe at a maximum of 100,000 feet. This does not imply that such a thickness is found in any one place, but that if the maximum thicknesses of each of the subordinate divisions be added together, they will amount to that sum. In this country more than 30,000 feet of Palæozoic strata are exposed in the much folded and profoundly denuded Appalachian Mountains, but in the Mississippi valley they attain only a fraction of that thickness. These rocks are, in the vast majority of cases, of marine origin, but some fresh-water beds are known, and very extensive swamp deposits have preserved a record of much of the land life of the era, especially of its later portions. That there must have been land surfaces is abundantly shown by the immense thickness and extent of the strata, all of which were derived from the waste of the land. Both in Europe and in North America the land areas were prevailingly toward the north and are doubtless indicated, in part, by the great regions of the pre-Cambrian metamorphic rocks. The general character of the Palæozoic beds shows that they were, in large measure, laid down in shallow water in the neighbourhood of land. Their great thickness indicates, further, the enormous denudation which the land areas underwent. The calculation has not been made for this country, but for Great Britain Geikie states that the lower half of the Palæozoic group represents the waste of a plateau cut down to base-level, larger than Spain and 5000 feet high.

Very wide-spread disturbances of the earth's crust before the beginning of the Palæozoic era and at its close have produced well-nigh universal unconformities with both the underlying pre-Cambrian and the overlying Mesozoic rocks; at only a few points are transitional series found.

Very early in Palæozoic time were established the main geographical outlines which dominated the growth of the North American continent,—a growth which was, for the most part, steady and tranquil. These conditions may be briefly stated as the formation of a great interior continental sea, divided from the Atlantic and the Pacific by more or less extensive and variable land areas. There are thus three principal regions of continental development: those of the Atlantic and Pacific borders and the interior. In addition, the eastern border is subdivided by pre-Cambrian ridges into subordinate areas of deposition. At the present time the surface rocks over the eastern half of the continent are prevailingly Palæozoic, extending chiefly southward and southeastward from the great pre-Cambrian mass of the north.

Palæozoic time was of vast length, probably exceeding that of the combined Mesozoic and Cenozoic eras.

The subdivisions of the Palæozoic are very clearly marked, locally often by unconformities, but on a wide scale by the changes in the character of the fossils. There is some difference in the practice concerning these divisions, not as to their limits or order of succession, but merely as to their rank, whether certain ones should be called systems (periods) or series (epochs). This is a difference more about names than facts. The successive steps of organic and geographical development are best displayed by dividing the group into six systems, or periods, which are as follows, beginning with the oldest: 1. Cambrian; 2. Ordovician; 3. Silurian; 4. Devonian; 5. Carboniferous; 6. Permian. By many geologists the Ordovician and Silurian are comprised in one system, and the Carboniferous and Permian in another; but the present tendency is in favour of maintaining all six as equal in rank. It must not be supposed that these systems represent equal spaces of time as measured by the thickness of rocks, or equal geographical extent; on the contrary, they are very unequal in both these respects. The classification means that the six systems, or periods, stand for approximately equivalent changes in the character of the animals and plants.

Palæozoic Life possesses an individuality not less distinctly marked than that of the group of strata, which demarcates it very sharply from the life of succeeding periods, and gives a certain unity of character to the successive assemblages of plants (*floras*) and of animals (*faunas*). The era is remarkable both for what it possesses and what it lacks. Among plants, the vegetation is made up principally of Cryptogams, seaweeds, ferns, club-mosses, and horsetails. Especially characteristic are the gigantic, tree-like club-mosses and horsetails, which are now represented only by very small, herbaceous forms. The only flowering plants known are the Gymnosperms, the Cycads and their allies; no Angiosperms have been discovered. Palæozoic forests must have been singularly gloomy and monotonous, lacking entirely the bright flowers and changing foliage of later periods.

The Palæozoic fauna is largely made up of marine invertebrates, in the earlier periods entirely so, *i.e.* so far as we have yet learned, though land life surely began before the oldest records of it yet discovered. Corals, Echinoderms (especially Crinoids, Cystideans, and Blastoids), Brachiopods, Mollusca (particularly the Nautiloid Cephalopods), and the crustacean group of Trilobites are the most abundant and characteristic types of animal life. Insects, centipedes, and spiders were common toward the end of the era. Cambrian rocks contain no fossil vertebrates, but they make their appearance in the Silurian, and perhaps earlier. For long ages the only vertebrates were fishes and certain low types allied to the fishes, but at the end of the Devonian and in the Carboniferous appeared the Amphibia, followed in the Permian by true Reptiles. Teleosts, such as make up by far the largest part of the modern fish-fauna, both marine and fresh-water, as well as birds and mammals, are entirely absent from the Palæozoic.

The overwhelming majority of Palæozoic species, and even genera, fail to pass over into the Mesozoic, and even in the larger groups which continued to flourish, almost always a more or less complete change of structure occurs, so that Palæozoic corals, Echinoderms, and fishes, for example, are very markedly distinct from those which succeeded them. The difference is generally in the direction of greater primitiveness of structure in the older forms, Palæozoic types standing in somewhat the same relation to subsequent types as the embryo does to the adult.

The Palæozoic climate appears to have been mild and equable on the whole, very much the same kinds of animals and plants occurring in high as in low latitudes. In short, we can detect no evidence of climatic zones as being distinctly marked in those periods. Certain remarkable exceptions to this rule will be noted in their proper place.

THE CAMBRIAN PERIOD

The rocks older than the coal measures were for a long time heaped indiscriminately together, under the name of Greywacke, or Transition Rocks, and were little regarded by geologists. About 1831, the problem of these ancient rocks was attacked by two eminent English geologists, Sedgwick and Murchison, who soon brought order out of the chaos. There was much discussion and dispute as to the limits of the systems into which the Greywacke should be divided, and as to the names which should be given to them. The oldest fossiliferous strata were by Sedgwick called *Cambrian* (from the Latin name for Wales), but were included by Murchison in his Lower Silurian. The latter example was long followed by most geologists, but the advance of knowledge has fully vindicated the claim of the Cambrian to rank as a distinct system. The divisions of the American Cambrian are as follows: —

3. Upper Cambrian, Potsdam Epoch, *Olenus* Fauna.
2. Middle Cambrian, Acadian Epoch, *Paradoxides* Fauna.
1. Lower Cambrian, Georgian Epoch, *Olenellus* Fauna.

American. — In North America, Cambrian rocks are not exposed at the surface over very large areas, being, for the most part, deeply buried under later sediments. Their maximum thickness, so far as known, does not exceed 12,000 feet, but this may be considerably increased at the expense of the Algonkian. While not forming extensive areas of the present surface, Cambrian strata are very widely distributed over the continent, usually resting unconformably upon the plicated and metamorphosed rocks of the Archæan and Algonkian. These strata are found in the pre-Cambrian depressions, from the Adirondacks to Newfoundland, and along the flanks of the Appalachian uplift, from the St. Lawrence to Alabama. They also fringe Archæan or Algonkian areas in other regions, as in Wisconsin, Missouri, Texas, in the Rocky Mountain chain, from Colorado to British Columbia, and in the mountains of Nevada. Cambrian beds are exposed in the Colorado Cañon, and doubtless would be found throughout the larger part of the continent, were the overlying beds stripped away.

So far as they are accessible to observation, the Cambrian rocks are chiefly such as are laid down in shallow water near shore, conglomerates, sandstones, shales (with some limestones), which are ripple-marked in a way that betrays their shoal-water origin. There are also some areas of deeper water accumulations, found in the limestones of western Vermont, Nevada, and British Columbia.

During Cambrian times the sea was slowly advancing over the land in North America, and the geography of the continent was very different at the close of the period from what it had been at the beginning. In the Lower Cambrian the land areas are inferred to have been somewhat as follows: First, there was the great northern mass of crystalline Archæan and Algonkian rocks, but this was probably much more extensive than the present exposures of pre-Cambrian rocks would indicate. It probably covered the whole Mississippi valley down to latitude 30° N. and extended westward beyond the Rocky Mountains. Long, narrow strips of land, alternating with narrow sounds, occupied part of New England and the maritime provinces of Canada, while an Appalachian land, whose western line is marked by the present Blue

Ridge, extended eastward an unknown distance into the Atlantic. On the *western* shore of the Appalachian land was a narrow arm of the sea, which opened both to the north and south and separated this land area from the great mass of the continent. The site of the Sierra Nevada was occupied by a long, narrow land, running from Puget Sound to Mexico, and another such area was found in eastern British Columbia. The Great Basin region was under water. Around these shores were laid down the coarser deposits of the Lower Cambrian, with great masses of shales and some limestone in deeper water.

In the course of time the continent was slowly depressed, the sea gradually advancing from the south during the Middle Cambrian, and reaching its greatest extension in the Upper. Toward the close of the period a large part of the continent had been submerged and, in particular, a vast interior sea had been established over the Mississippi valley.

Cambrian in Other Continents. — In Europe the Cambrian rocks are even more fully developed than in North America, having in Wales a thickness of 20,000 feet of conglomerates, sandstones, shales, slates, and quartzites. These rocks bear witness to their shallow-water origin and were deposited on a slowly sinking sea-bottom. The Cambrian rocks have their maximum thickness along the western side of the continent, being four times as thick in Wales and Spain as in Germany and Bohemia. In Russia the rocks of this period are remarkable for their unconsolidated character; at the base are 300 feet of plastic clays, which look as though they had just been abandoned by the sea. In central Russia the Cambrian dies out and the Ordovician strata rest directly upon the Archæan. Cambrian rocks occur extensively in northeastern China, in India, in Australia, and in the Argentine Republic.

CAMBRIAN LIFE

The Cambrian fauna is of extraordinary interest, because it is the most ancient that we know, but the most superficial examination of it shows that it cannot represent the beginnings of life upon our planet. Almost all the great types of invertebrates are already present and very definitely characterized, indicating that life had been differentiating for a vast period before the lowest Cambrian rocks had been laid down. As compared with the faunas of other Palæozoic periods, that of the Cambrian is very scanty, but our knowledge of it has been greatly increased of late and may be expected to increase in the future.

Though the successive Cambrian faunas have a very uniform distribution over wide areas, there are already indications of local differences which mark out faunal provinces; thus, the Middle Cambrian fossils of Newfoundland are more similar to those of Europe than to those of the Appalachian and interior regions of America. The same fauna recurs in Alabama, but not further north in the Appalachians. The advance of the sea gave to Upper Cambrian life a wider and more uniform distribution over the continent than to that of the Lower.

Of **Plants** nothing is surely known; certain marks on the bedding planes of strata have been regarded as seaweeds, but they are too obscure for determination.

The fauna is principally made up of Brachiopods and Trilobites, but many other types are represented also.

Spongida. — Siliceous Sponges are not uncommon.

Cœlenterata. — The Hydrozoa are believed to be represented by the *Graptolites*, a series of forms which are confined to the older Palæozoic rocks. These curious animals formed compound colonies, with cells for the different individuals arranged on one or more sides of a stem, and of a great variety of form; some are straight, others spiral, and though commonly found in single branches, some specimens have many branches united. (See Pl. II, Fig. 3, p. 383.) The skeleton was horny, and so the fossils appear as mere markings on the rocks, but often in excellent preservation. The systematic position of the Graptolites is entirely uncertain, though they are usually referred to the Hydrozoa.

Other Hydrozoa are the jelly-fish, of which recognizable casts have been found in large numbers.

It is still a question whether *Corals* were present in the Cam-

[illegible], certain fossils which by some authorities are called corals are by others regarded as sponges. At all events, they are not conspicuous elements in the fauna.

Echinodermata. — The Echinoderms are rare and are principally Cystids, a very primitive grade of the type; true Crinoids and Star fishes appear before the close of the period.

Worms. The presence of marine worms is indicated by tracks and borings in the sands which have now consolidated into hard rocks.

Arthropoda. — The only known Cambrian Arthropods are the *Crustacea*, and of these much the most abundant group is that of the *Trilobita*, which are altogether confined to the Palæozoic rocks and are by far the most important of Cambrian fossils. It is only within recent years that the systematic position of the Trilobites has been established through the fortunate discovery of specimens with their appendages attached (see Fig. 138). Trilobites have a more or less distinctly three-lobed body, at one end of which is the head shield, usually with a pair of fixed compound eyes, at the other end is the tail-shield, and between the two shields is a hinged or jointed body made up of a variable number of movable segments. The Trilobites display an extraordinary variety in form and size, in the proportions of the head and tail-shields, in the number of free segments, and in the development of spines. Already in the Cambrian this wealth of forms is notable, though far less so than it became in the Ordovician. As compared with those of later times, the Cambrian Trilobites are marked by the generally very small size of the tail shield, the large number of free segments, and their inability to roll themselves up. Some of [illegible] are very large (from 10 inches to 2 feet [illegible] also has large species, while *Agnostus* is ex[illegible]

[illegible] for Cambrian stratigraphy [illegible] the three divisions of the system [illegible] of these crustaceans. [illegible]

[illegible] found in the Cambrian: the *Ostracoda*, little bivalve forms, whose shells look deceptively like those of molluscs; and the *Phyllopoda*, which have a large shield on the head and thorax, and a many-jointed abdomen.

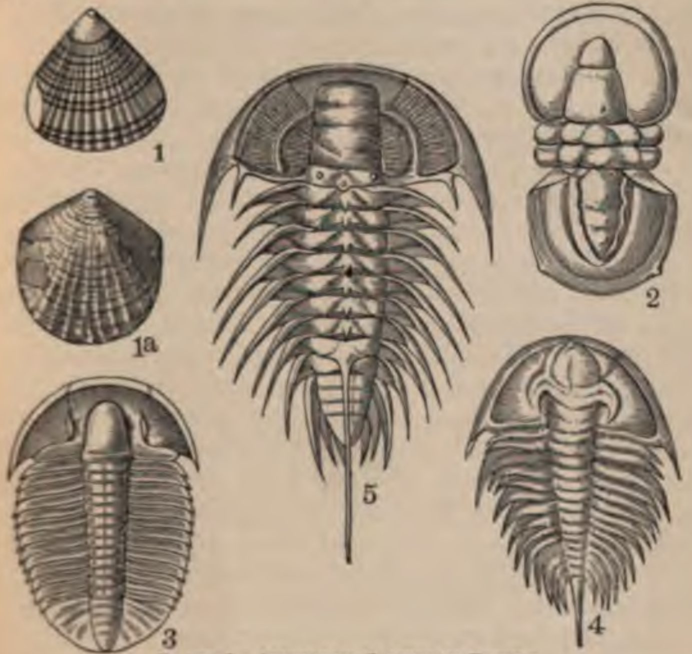

Plate I. American Cambrian Fossils

1. Lingulella cœlata, 2/1. (Walcott.) 2. Agnostus interstrictus, 3/1. (Walcott.) 3. Conocoryphe Kingi. (Meek.) 4. Elliptocephalus Thompsoni. (Walcott.) 5. Olenoides typicalis. (Walcott.)

Brachiopoda. — These are among the most abundant of Cambrian fossils; most of them belong to the lower order of the class (*Inarticulata*), in which the shells are mostly horny and the two valves are not articulated together by a hinge. The horny-shelled *Discina* and *Lingulella* are of great interest, for they have persisted through all the changes and vicissitudes of the earth down to the present day, with hardly any modification. The second order of Brachiopods, the *Articulata*, which have calcareous shells connected by an elaborate hinge, became more common in the Upper Cambrian. They soon grow vastly more numerous than the Inarticulata, and throughout the post-Cambrian divisions of the Palæozoic their shells are found in incalculable numbers.

The **Mollusca** are already represented by their principal divisions. The *Pelycypoda*, or Bivalves, are of very small size and found very scantily; their variety and relative importance have gone on increasing ever since Cambrian times. *Gastropoda* occur in small numbers, especially in the Upper Cambrian. Fossils referred, with some doubt, to the *Pteropoda* are among the most frequent of shells found in these rocks, but display no great variety. The *Cephalopoda*, which are the highest group of molluscs, are at present represented by two suborders; in one, the squids and cuttle-fishes (*Dibranchiata*), the shell is rudimentary and internal; while in the other (*Tetrabranchiata*) the shell is external. The latter kind of shell is divided by transverse *septa* into chambers, which are connected by means of a tube, the *siphuncle*, the animal living only in the terminal chamber at the mouth of the shell. The only living representative of this group is the pearly Nautilus, but throughout Mesozoic and Palæozoic time there was a great variety of these chambered shells. In the Cambrian the Cephalopods are very few and almost confined to the uppermost part of the system.

The Cambrian fauna displays steady progress, being distinctly more advanced in the upper than in the lower division. The Middle Cambrian fauna, so far as it is yet known, has not nearly so many species as the Lower, but this is doubtless due to unfavourable conditions of preservation.

CHAPTER XXIII

ORDOVICIAN (OR LOWER SILURIAN) PERIOD

Murchison divided his great Silurian system primarily into two parts, Upper and Lower. This method of classification is generally followed even at the present day, although it is widely recognized that the most decided break in the entire Palæozoic group is the one between these divisions. In 1879 Lapworth proposed to give due emphasis to this distinction by erecting the Lower Silurian into a separate system, the *Ordovician*. The name is taken from the *Ordovici*, an ancient British tribe which dwelt in Wales during Roman times. Lapworth's example is now largely followed in England and the United States, but on the continent of Europe the name *Silurian* is still retained for both systems.

The classification and subdivision of the American Ordovician were first worked out in the state of New York, and consequently the New York scale serves as a standard of reference for the rest of the continent. It is given in the following table from Dana: —

Ordovician System.	2. Trenton Series.	3. Hudson or Cincinnati Stage.
		2. Utica Stage.
		1. Trenton Stage.
	1. Canadian Series.	2. Chazy Stage.
		1. Calciferous Stage.

The passage from the Cambrian to the Ordovician was a gradual one, not marked either in North America or in Europe by any decided physical break, but by a change in the character of the fossils. By the end of the Cambrian period a vast interior sea had been established over what is now the Mississippi valley. This great sea was separated from the Atlantic by the Appalachian land, and on the west islands of unknown size demarcated it from the Pacific. The Ordovician rocks accumulated in the Interior Sea were principally limestones and dolomites, while at the east extensive sandstones and slates were formed at the beginning and toward the end of the period. Ordovician rocks have a much wider extension than would appear from their surface distribution, for they are generally buried under sediments of a later date. In the west, for example, they are exposed at the bottom of many deep cañons, lying beneath thousands of feet of younger beds. In the southwest of the United States was a land area of unknown extent. In the Grand Cañon section no strata occur between the Cambrian and the Carboniferous, while from Mexico no rocks older than the Carboniferous have been reported.

Around the northern pre-Cambrian land, in New York and Canada, was formed the *Calciferous*, a limestone, generally magnesian and often sandy or cherty, which extends southward through New Jersey and Pennsylvania, while equivalents of it are found in the magnesian limestones of Iowa, Missouri, and Michigan.

Deepening waters next gave opportunity for the formation of limestones (*Chazy*) which grew to a vast extension, especially the great formation called the *Trenton*, which is developed in New Brunswick, New York, Canada, the upper Mississippi valley, and in the Rocky Mountains. Toward the end of the Ordovician period there was a change in the eastern part of the Interior Sea, whereby the clear waters became charged with fine mud and clay, which now form a great mass of shales and slates (*Utica* and *Hudson*). These rocks are thickest toward the east, extending from the St. Lawrence along the Appalachian uplift into east Tennessee, where they become much thinner and are in many places represented by shaly limestones, and westward into Indiana. The effects of the change were very widely felt.

Ordovician rocks, prevailingly limestones, are also extensively displayed in the western mountain ranges, the Rockies, Uintas, Wasatch, and others; they fringe the western side of the great northern pre-Cambrian area and recur in the islands of the Arctic Ocean.

Foreign. — In Europe the Ordovician rocks appear to have been laid down in two distinct seas separated by a ridge of land. The northern area extends from Ireland far into Russia, while the southern is represented by numerous scattered masses. These rocks cover a much wider surface than do the Cambrian. In Great Britain, especially in Wales, they form very thick masses of shales and slates, with but little limestone, intercalated with much volcanic lava and tuff. In Scandinavia these rocks are nearly horizontal limestones and shales, and in Russia they cover very large areas and are so perfectly undisturbed that many are still incoherent sediments. In the southern sea were laid down the Ordovician strata of Bohemia, Germany, northwestern and central France, Spain, Portugal, Sardinia, and Morocco.

The very marked difference between the fossils of the two great European areas, and the fact that the Ordovician fossils of other continents agree with those of northern Europe, while those of the southern district are peculiar, indicate that the latter region was a partially closed sea, which occupied the Mediterranean basin, though extending far beyond its present limits.

Asia appears to have been principally dry land during the Ordovician, but with a broad Indo-Chinese sea covering its eastern shore. Africa has Ordovician rocks only in the Mediterranean region; in the southern part of the continent nothing older than Devonian is known. The Australian continent of Cambrian times was partially submerged in the Ordovician, and strata of this date were laid down in New Zealand, Tasmania, and the southern part of Australia. But little of South America was submerged and that continent may have been considerably larger than at present. Rocks of this system are known only from Bolivia and Argentina.

Close of Ordovician. — The period was a time of tranquil deposition of sediments, with some oscillations of level and changes in the depth of water and position of the shore line, as indicated by the alternations of the strata. At the close of the period came a time of wide-spread disturbance, upheaval, and mountain making, the traces of which may still be plainly observed in North America and Europe, especially along the Atlantic slope of each continent. In Nova Scotia and New Brunswick the Silurian strata lie unconformably upon the upturned Ordovician. Along the line between New York and New England the Taconic range was upheaved, its rocks greatly compressed, plicated, faulted, and metamorphosed. Many of the crystalline schists of this region, it has been proved, were derived from the metamorphosis of Cambrian and Ordovician sedimentary rocks. Evidences of this disturbance have been traced as far south as Virginia. The effects of the upheaval were not felt in the northern part of the Gulf of St. Lawrence, for on Anticosti Island the great limestone, which was begun in Ordovician times, continued without a break into the Silurian. The disturbance was along a line of especially thick accumulations, as appears from the comparative measurements of the same strata in different areas. Westward over the Interior Sea, the upheaval was, for the most part, of slight amount, so that in this region there are no very marked unconformities between the Ordovician and the overlying Silurian. Some narrow strips of land were added to the margin of the Cambrian coasts, and on a line running through southern Ohio, Kentucky, and Tennessee a low, broad arch was forced up by lateral compression. This is called the "Cincinnati anticline."

In Europe the disturbances which brought the Ordovician to a close produced their maximum effects in England, Wales, and the Highlands of Scotland, where the thickness of the sediments is greatest. In these regions the Ordovician beds are folded and often greatly metamorphosed, the Silurian strata lying upon their upturned edges.

The Life of the Ordovician

Ordovician life displays a notable advance over that of the Cambrian, becoming not only very much more varied and luxuriant, but also of a distinctly higher grade. During the long ages of the period also very decided progress was made, and when the Ordovician came to its close, all of the great types of marine invertebrates and most of their more important subdivisions had come into existence. In a general way the life of the Ordovician is an expansion of that of the Cambrian, though but little direct connection between the two can yet be traced, and evidently there were great migrations of marine animals from some region which cannot yet be identified. Several groups of invertebrates attained their culmination and began to decline in the Ordovician, becoming much less important in subsequent periods. Thus the Graptolites, the Cystidean order of Echinoderms, the Pteropods among Molluscs, and the Trilobites were never so abundant and so varied as during this period.

Plants. — In America no plants above the grade of seaweeds have been discovered, but in Europe a few of the higher Cryptogams are doubtfully reported. The flora of the Devonian, however, renders it highly probable that land plants were already well advanced in the Ordovician, and their remains may be discovered at any time. This must remain a matter of accident, for the known Ordovician rocks are all marine, which is not a favourable circumstance for the preservation of land plants. Such discoveries have, indeed, already been reported, but the evidence for them is not satisfactory.

Foraminifera and Radiolaria have been found in sufficient numbers to prove that they were abundant in the Ordovician seas.

Spongida. — Sponges are much more numerous and varied than in the Cambrian. Of course it is only those sponges with skeletons of lime or flint which can be well preserved in the fossil state, and of these the Ordovician has many (Pl. II, Fig. 1). The horny sponges, of which the common bath sponge is a familiar example, are necessarily much rarer and less satisfactory as fossils.

Cœlenterata. — The *Graptolites* are very numerous and varied, wherever conditions are favourable to their preservation, as in fine-grained rocks with smooth bedding planes. The Ordovician is the time of their culmination and is especially characterized by the double forms, with rows of cells on both sides of the stem (see Pl. II, Figs. 2, 3, 4). So abundant are the Graptolites that in many parts of the system they are almost the only fossils and are employed to divide the substages into zones. The few and doubtful Cambrian *Corals* are succeeded by a considerable number of Ordovician genera and species. Like other Palæozoic Corals, these are characteristically different from the reef-builders of the present day in showing a marked bilateral symmetry and having the septa arranged in multiples of four (*Tetracoralla*). Large, solitary cup-corals, like *Streptelasma*, and compound colonies, like *Favistella* and *Columnaria*, are examples of the range of differences among these early corals.

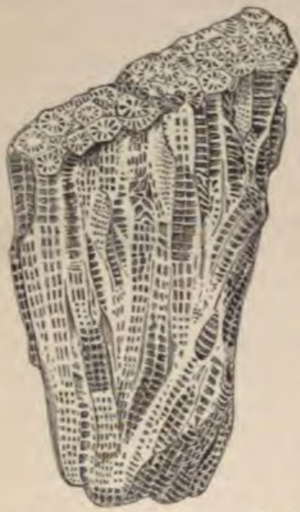

FIG. 137. — Ordovician Coral. *Favistella stellata*. Hudson Stage, New York. (Hall.)

The **Echinodermata** have greatly increased in importance, and except the Echinoids, all the main subdivisions of the group are represented. The *Cystidea*, which we have already found in the Cambrian, attain their greatest development in the Ordovician. In these curious animals the body is either irregularly shaped, or symmetrical, with a short, tapering stem, by which the animal was attached to the sea-floor, and weakly developed arms. The body, or calyx, is made up of a number of calcareous plates; when these plates are very numerous, they are of irregular size and arrangement (Pl. II, Fig. 6), while the forms with few plates have them of a definite number, size, and shape (Pl. III, Fig. 1). Some of the more regular Cystidea have much resemblance to the true *Crinoids*. The latter make their first appearance in the upper part of the Cambrian, but in the Ordovician they greatly increase in numbers and importance, though less abundant than they afterwards became. These animals (Pl. II, Fig. 5) have a symmetrical calyx, with long, branching arms; the number and arrangement of the component plates are definite and characteristic for each genus. Most, but not all, of the Crinoids have a long, jointed stem, by which they were attached to the sea-bottom.

Asteroids (star-fishes) and *Ophiuroids* (brittle-stars), which had likewise come in before the end of the Cambrian, increase in the Ordovician. A new order of Echinoderms, the *Echinoidea*, or Sea-urchins, first appear in the Ordovician, being represented by very primitive forms.

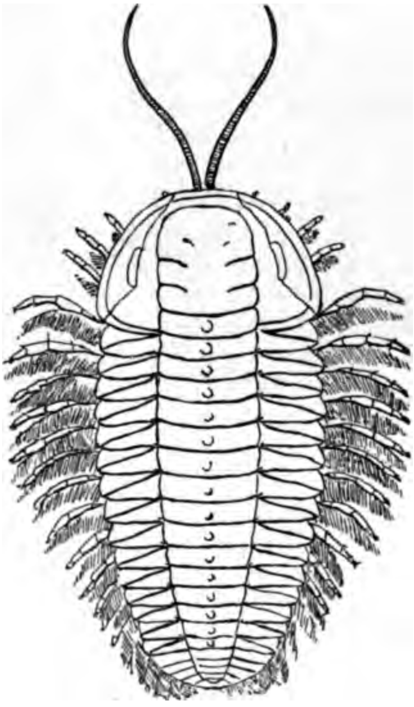

FIG. 138. — Ordovician Trilobite. *Triarthrus Becki*, enlarged restoration showing appendages. (Beecher.) Utica Stage, New York.

Arthropoda. — The Trilobites increase very greatly in the number of genera and species, and most of the Cambrian genera are replaced by new ones. This is the period in which the group of Trilobites attains its highest development, gradually declining afterward and becoming extinct with the close of the Palæozoic. The most characteristic and widely spread genera of Ordovician Trilobites are: *Asaphus* (Pl. II, Fig. 13), *Illænus*, *Triarthrus* (Pl. II, Fig. 15), *Calymene* (II, 14), *Trinucleus* (II, 16), *Dalmanites*, etc. These genera differ in aspect from those of the Cambrian in their much larger tail-shields, in their ability to roll themselves up (see II, 14), and in their larger and better developed, faceted eyes.

Other Crustacea mark great advances in the Ordovician. Thus, in the upper part of the system we find the first of the *Cirripedia*, or Barnacles, a degenerate, sedentary type, and the first of the *Eurypterida*, a group which is destined to a remarkable development in the Silurian and Devonian. *Ostracoda* (Pl. II, Fig. 17) and *Phyllopoda* undergo no marked change. That terrestrial animal life had already begun is demonstrated by the occurrence of a *Centipede*.

Brachiopoda. — These shells increase very largely in abundance and variety, the genera with hinged calcareous shells (Articulata) now gaining the upper hand and reducing the horny-shelled kinds to comparative insignificance. The most important genera are: *Orthis* (Pl. II, Fig. 7), *Orthisina*, *Leptæna*, *Strophomena* (Pl. II, Fig. 9), *Platystrophia* and *Rhynchonella*.

Bryozoa. — This is a group which has as yet yielded no representatives from the Cambrian, but appears in the Ordovician. The genera differ little from those which live in the modern seas.

Mollusca. — One of the most striking differences between the Ordovician and the Cambrian is the great advance made by the Molluscs in the former period. The Bivalves (*Pelycypoda*) are larger, more numerous, and more like modern forms (see Pl. II, Fig. 10). The *Gastropoda* likewise increase notably in size and in numbers, especially the spirally coiled shells like *Murchisonia* (Pl. II, Fig. 11) and *Pleurotomaria*; but neither Bivalves nor Gastropods had anything like the relative importance which they possess in modern times.

Much the most significant change in the Mollusca, however, is the great expansion of the *Cephalopoda*, a few of which appear in the uppermost Cambrian, but in the Ordovician have become one of the predominant elements in the marine life of the times. These forms are all *Nautiloids*, most nearly allied to the modern pearly Nautilus, with chambered shells, divided internally by simple

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Explanation of Plate II, p. 383. 1. Brachiospongia digitata, 1/4. 2. Dicranograptus ramosus, 1/2. (Hall.) 3. Diplograptus pristis. (Ruedemann.) 4. Phyllograptus typus. (Hall.) 5. Dendrocrinus polydactylus, 1/2. (Meek.) 6. Agelacrinus cincinnatiensis, 2/1. (Meek.) 7. Orthis lynx. 8. Rhynchonella capax. 9. Strophomena alternata. 10. Ambonychia radiata, 2/3. (Hall and Whitfield.) 11. Murchisonia Milleri, 2/3. (Hall.) 12. Orthoceras Duseri, 1/2. (Hall and Whitfield.) 13. Asaphus gigas, 1/3. (Hall.) 14. Calymene callicephala, 2/3. (Meek.) 15. Triarthrus Becki, 2/3. (Hall.) 16. Trinucleus concentricus. (Hall.) 17. Leperditia fabulites. (Ulrich.)

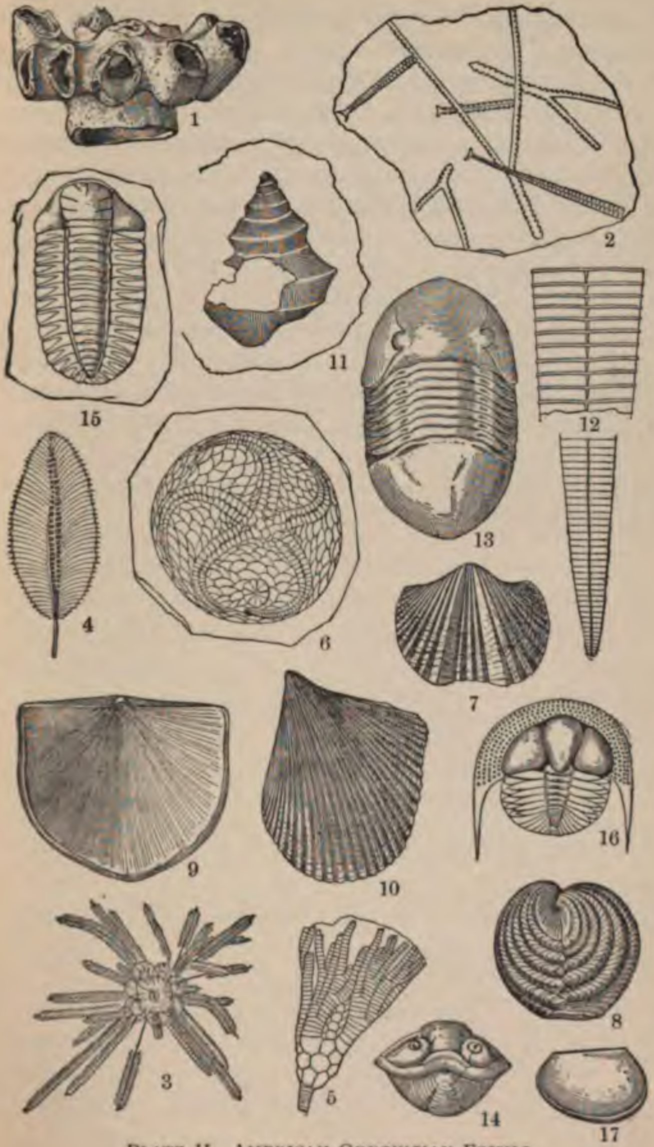


PLATE II. AMERICAN ORDOVICIAN FOSSILS

septa. The commonest shell of this type is *Orthoceras*, which is a straight and very elongate cone (Pl. II, Fig. 12) and sometimes attains a length of 10 feet; the genus persists throughout the Palæozoic and into the Mesozoic. *Endoceras*, which likewise has a straight shell, with a curiously complex siphuncle, is confined to the Ordovician. Besides these straight forms we find curved shells like *Cyrtoceras*, shells like *Lituites*, coiled at one end, with a long, straight terminal portion, resembling an Orthoceras with its smaller end rolled up into a coil. Others again, like *Trocholites*, have the shell coiled in a close, flat spiral.

Vertebrata.—The curious, mail-clad *Ostracoderms*, primitive vertebrates which somewhat resemble the fishes in appearance, have been reported from Ordovician sandstones of Colorado. As these remains are very imperfect and as the geological position of the beds has been questioned, description of the Ostracoderms will be deferred till a later chapter. Teeth of true fishes have been found in the Ordovician of Europe.

CHAPTER XXIV

THE SILURIAN (UPPER SILURIAN) PERIOD

THE name *Silurian*, like Cambrian and Ordovician, refers to Wales. The term was proposed by Murchison in 1835 for a great system of strata older than the Devonian, and was taken from the *Silures*, another ancient tribe of Britons which inhabited part of Wales. Murchison gave great extension to his Silurian system, including in it most of Sedgwick's Cambrian, but, as already pointed out, the present tendency is to divide this vast succession of rocks into three systems of equivalent rank. It is unfortunate, and even unjust, that Murchison's term should not have been retained for the more important and widely developed lower division, now called the Ordovician, rather than for the upper division.

As in the Ordovician and Devonian, the New York classification, given in tabular form below, is the standard of reference for the American Silurian.

Silurian System.	3. Lower Helderberg Series.	3. Upper Pentamerus Stage.
		2. Shaly Limestone Stage.
		3. Lower Pentamerus Stage.
	2. Onondaga Series.	Salina and Water-lime beds.
	1. Niagara Series.	3. Niagara Stage.
		2. Clinton Stage.
		1. Medina Stage.

American. — The disturbance which closed the Ordovician does not appear to have materially enlarged the extent of the continent, and at the beginning of the Silurian the general disposition of land and water was much what it had been before. A narrow strip of coast lands had been added to the shore of the northern pre-Cambrian land mass, converting Minnesota, Wisconsin, much of the province of Ontario, northern New York, and New Jersey, and western New England, into permanent land. The Appalachian land was enlarged and connected with the northern area, shutting off the straits which had formerly separated the two areas and had joined the Interior Sea with the Gulf of St. Lawrence. Southern Ohio and central Kentucky and Tennessee had been uplifted into one or more considerable islands, which shut off the northeastern portion of the Interior Sea as a partially closed gulf, while another island occupied southern Missouri. What changes affected the land masses of the far West and Southwest cannot yet be definitely determined, but it is probable that they were enlarged.

The Silurian rocks are much better developed and far thicker in the East, especially along the Appalachian range, where they attain great thickness, than in the interior or western regions, for they thin out or are wanting over large parts of the latter. So far as they have been identified, these rocks were laid down in the Interior Sea or in the narrow channels which still extended from the Gulf of St. Lawrence southward into New England.

The period opened with the formation in the East of a thick conglomerate of quartz pebbles and sand, the *Oneida* (a substage of the Medina). This conglomerate is extensive in central New York, thinning toward the eastern shore line, but very thick along the Appalachian ranges as far south as Tennessee. Owing to its hardness and resistant qualities, it forms the crest of many of the mountain ridges, as of the Kittatinny, at the Delaware Water Gap. Farther west and overlying the conglomerate is a great mass of sandstone, the *Medina*, which was accumulated in very shallow water, for it is abundantly ripple-marked. The sandstone extends westward from central New York, thinning out to a belt of shale in Ohio; reduced to a thickness of 300 to 400 feet in Ontario, it does not reach Michigan, but is very thick in eastern Pennsylvania (1800 feet). No equivalent of these beds is known in the interior.

In New York and Pennsylvania the sandstone is followed by a series of shales and shaly sandstones with some beds of limestone, the *Clinton*, which is much more widely extended, reaching southward along the Appalachians to Georgia, and westward as far as

Wisconsin. The sea evidently deepened to the westward, for here the Clinton is represented by limestones. Next came a time of limestone making on a great scale (the *Niagara*), indicating a general deepening of the water, even to the eastward. The gradual nature of the change is shown by the fact that in western New York the lower part of this stage is a shale, with limestone above. This arrangement is beautifully displayed in the gorge of the Niagara River (see p. 100), and to it is due the continued verticality of the falls. In the East the Niagara limestone has little southward extension, not occurring even in Pennsylvania, but southwestward it stretches for nearly 1000 miles, to Wisconsin and thence over Illinois, Iowa, Missouri, and western Tennessee. It recurs in the Black Hills of South Dakota, and in Nevada is represented by the summit of a thick mass of limestone, which extends upward unbrokenly from the Trenton. The Niagara limestone is very largely made up of corals and in some places the ancient reefs may be identified. In the narrow channels to the northeastward, connected with the Gulf of St. Lawrence, were laid down the Niagara rocks which now are found in New England, New Brunswick, and Nova Scotia.

The next change was the separation, along the northern portion of the interior sea, of a series of salt-water lagoons, in which were deposited red marls and shales with gypsum and rock salt (*Salina*), from which are obtained the brines of New York, Ontario, and Ohio. These rocks are thickest in New York and Pennsylvania, thinning to the south and west. In part contemporaneous with the Salina is the *Water-lime*, so called because it is a hydraulic limestone and employed for making cement. It is a thinly bedded argillaceous and magnesian limestone, in places enclosing masses of gypsum. The Water-lime has much the same distribution as the Salina, but is thickest where the latter is thin.

A renewed change of level, this time a depression, brought the sea in again where the salt lagoons had been, extending it farther to the eastward at the same time. In this clearer and deeper sea were laid down the limestones of the *Lower Helderberg* series. The old channel between the Appalachian and the northern lands was probably reopened by this disturbance, by way of the upper Hudson and Lake Champlain, for near Montreal the beds of this series rest directly upon Ordovician strata (Utica shales). The channels reaching southward from the Gulf of St. Lawrence, which were extended by the depression, also received limestone accumulations, of which remnants still are found in Vermont, Maine, and the maritime provinces of Canada. Southward the principal area of the Lower Helderberg extends through Pennsylvania to Virginia, and it recurs in western Tennessee and Missouri, but has not been distinguished in Wisconsin or Illinois.

Silurian strata are not common in the Rocky Mountain region, and the persistence there of comparatively deep water from Ordovician times makes it very difficult to distinguish the series and stages which are so well marked in the East, and which were due to the oscillations of level and the changes in the character of sedimentation which occurred in the latter region.

Foreign. — The division into northern and southern areas which we found in the Ordovician, was maintained in Silurian times, and the southern sea was as peculiar in its animal life as it had been before, the northern being the typical Silurian which is found in the other continents. In the west of Ireland, Wales, northern England, and Scotland, Silurian beds accompany and overlie the Ordovician, but the much greater development of limestone points to a deepening of the water in those seas. The Wenlock limestone of Great Britain, which corresponds to the American Niagara, is, like the latter, largely coralline. In Scandinavia also there is a great development of Silurian limestones, which extend far into Russia. In the latter country the sea had retreated much from its extension in the Ordovician, except toward the southeast, where it was carried into Bessarabia. Most of the Russian Silurian was formed in an interior sea, connected with that of southern Europe. In the southern European countries, which display the Bohemian type of development, or *facies*, the Silurian rocks have nearly the same general distribution as the Ordovician. The two systems are also associated in the Arctic islands, in China, north

Africa, South America, and Australia. In all of these areas, as also in North America, the fossils resemble those of the northern European region, rather than those of the southern. In general the Silurian rocks are less extensively exposed at the surface than the Ordovician.

Close of the Silurian. — In North America the Silurian passed so gradually and gently into the Devonian, that it is difficult to draw the line between the two systems. Some disturbances, however, took place in Ireland, Wales, and the north of England, for in these localities the Devonian lies unconformably upon the Silurian. In other parts of Europe the transition was gradual.

The Life of the Silurian

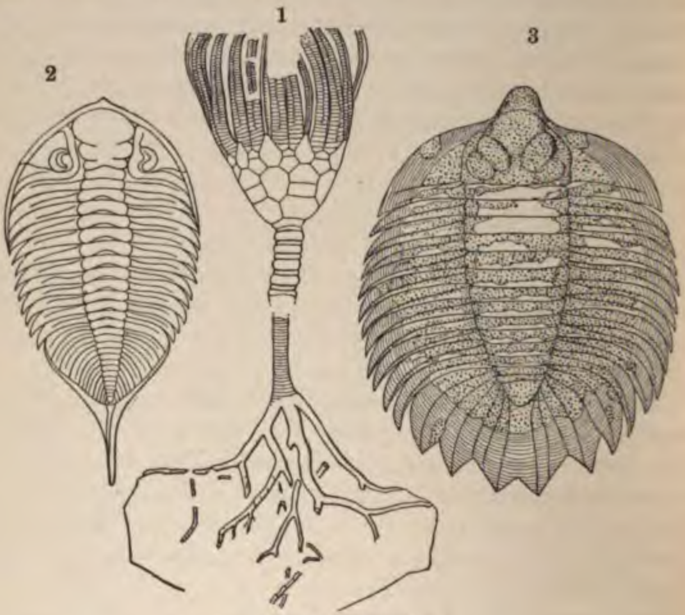
Silurian life is the continuation and advance of the same organic system as flourished in the Ordovician, certain groups diminishing, others expanding; and some new groups now make their first appearance.

Plants. — Our knowledge concerning the land vegetation of the Silurian is not much more definite than concerning that of the Ordovician. Most of the remains referred to land plants are of disputable character; the best authenticated is a fern (*Neuropteris*) from the Silurian of France.

Spongida are still common. A wide-spread form is *Astylospongia* (Pl. III, Fig. 1).

Cœlenterata. — The Graptolites have greatly diminished, especially the branching forms and those with two or more rows of cells. Those that persist are, for the most part, straight and simple (III, 2). The Hydroid Corals, on the other hand, such as *Heliolites*, become important elements of marine life and in the formation of the reefs. The true *Corals* likewise increase largely, and play a more important rôle than in the preceding period. The increase is principally in the enlarged number of species belonging to much the same genera. *Favosites* is a characteristic new genus (see III, 3), and *Halysites*, the chain coral, is much commoner than before.

Echinodermata. — In this group we observe a diminution of the *Cystidea*, but a marked increase of the *Crinoids*; *Eucalyptocrinus* (see Fig. 139/1) is a good example. Star-fishes also have grown more abundant. A new class of the Echinoderms now makes its first appearance, the *Blastoidea*. This class is extinct at present and its structure is not well understood; the group remains rare in the Silurian and Devonian, first becoming important in the Carboniferous. The Echinoids, or sea-urchins, which were commoner than before, have no arms, but a closed spheroidal or discoidal test, made up of calcareous plates, which in all the modern sea-urchins are arranged in just twenty vertical rows, and are closely fitted together by their edges, like a mosaic pavement. In the Palæozoic



SILURIAN FOSSILS

FIG. 139. — 1. Eucalyptocrinus crassus, 1/2. 2. Dalmanites limulurus. 3. Lichas Boltoni, 1/3. (After Hall.)

sea-urchins the number of rows of plates is either more or less than twenty; in some of the Silurian genera the plates are loosely fitted, and slightly overlapping, like fish-scales.

Arthropoda. — Among the Crustacea the Trilobites are still numerous, though decidedly less so than they were in the Ordovician; they represent, for the most part, new species of genera which have survived from the preceding period. The commonest genera are *Calymene*, *Illænus*, *Dalmanites* (Fig. 139/2), *Lichas* (Fig. 139/3); while newly added are the genera *Phacops*, *Proetus*, *Encrinurus*, etc. *Eurypterids* continue to increase in numbers and size, though not reaching their maximum in either respect until the Devonian. In these extraordinary Crustacea the head is very small and is followed by a long, tapering body, composed of thirteen movable segments; the last segment is either a pointed spine, as in *Eurypterus*, or a broad tail-fin, as in *Pterygotus*. Five pairs of appendages are attached to the head, the bases of four of which, on each side of the mouth, form the jaws, as in the existing horse-shoe crab. The first pair of appendages are either short and simple (*Eurypterus*, *Stylonurus*), or are much elongated, and armed with pincers (*Pterygotus*). The fifth pair are either very long, or enlarged to serve as swimming paddles. The first body-segment carries a pair of apron-like appendages, with a narrow median extension, but the other segments have no appendages. The horse-shoe crabs find their most ancient representative in the genus *Hemiaspis* of the European Silurian. Other Crustacea are much as in the preceding period.

Scorpions have been found in the Silurian of Europe and America, and some remains of *Insects* in the former continent. These animals prove the existence of a contemporaneous land vegetation, and confirm the doubtful evidence of the Ordovician and Silurian plants.

Bryozoa are quite abundant, and contribute in an important way to the growth of the coral reefs.

Brachiopoda continue to be present in multitudes, but with a distinct change in dominant genera from those which were commonest in the Ordovician. Especially characteristic is the increase in the families of the *Spiriferidæ*, *Pentameridæ*, and *Productidæ*, all

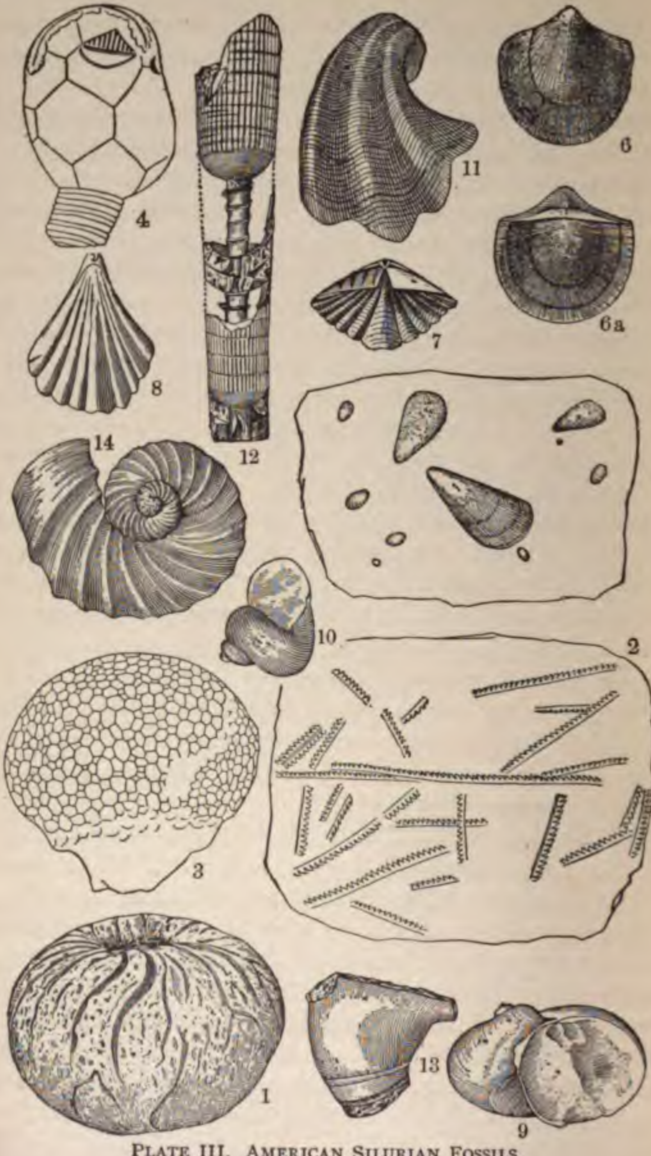


PLATE III. AMERICAN SILURIAN FOSSILS

of which continue prominent in the Devonian. The most important genera are *Atrypa*, *Spirifera* (III, 7), *Pentamerus*, and *Rhynchotreta* (III, 8).

Mollusca. — The Bivalves show no very significant changes from the Ordovician, but the Gastropods, especially such forms as *Capulus* (Pl. III, Fig. 11) increase decidedly; other well represented genera of these shells are *Platyostoma* (III, 9) and *Cyclonema* (III, 10). *Pteropods* are smaller and less numerous than before; a very common form is the little nail-shaped shell, *Tentaculites*, which is doubtfully referred to this group, but may belong to the Worms. Among the Cephalopods *Orthoceras* (III, 12) continues abundant, but *Lituites* has grown less common and *Endoceras* has disappeared, while coiled shells like *Trochoceras* (III, 14) are not infrequent. The shells with curiously contracted mouth openings, like *Phragmoceras* (III, 13) are more commonly found than in the Ordovician.

Vertebrata. — The remains of Ostracoderms and Sharks show that Vertebrates certainly existed in the Silurian, but the known remains are so fragmentary that a description of these curious fishes and fish-like animals will be reserved for the following chapter.

Explanation of Plate III, p. 392. 1. Astylospongia præmorsa. 2. Graptolithes clintonensis. 3. Favosites Forbesi. 4. Lepadocrinus Gebhardi. 5. Lingulella cuneata. 6. Orthis elegantula. 7. Spirifera crispa. 8. Rhynchotreta cuneata. 9. Platyostoma niagarense. 10. Cyclonema cancellatum. 11. Capulus angulatus. 12. Orthoceras annulatum, 1/2. 13. Phragmoceras parvum, 1/2. 14. Trochoceras desplainense, 1/2. (Fig. 1 after Roemer, Figs. 2–14 after Hall.)

CHAPTER XXV

THE DEVONIAN PERIOD

THE name *Devonian*, taken from the English county Devonshire, was proposed by Sedgwick and Murchison in 1839; it has found universal acceptance and has passed into the geological literature of all languages.

As in the Ordovician and Silurian, and for the same reason, the divisions of the New York Devonian are taken as the standard of reference for North America.

Devonian System.	Upper Devonian.	4. Chemung Series.	2. Chemung Stage. 1. Portage Stage.
	Middle Devonian.	3. Hamilton Series.	2. Hamilton Stage. 1. Marcellus Stage.
	Lower Devonian.	2. Corniferous Series.	2. Corniferous Stage. 1. Schoharie Stage.
		1. Oriskany Series.	

DISTRIBUTION OF THE DEVONIAN

American. — In North America the passage from the Silurian to the Devonian is very gradual, the former drawing to its close without disturbance; and there is still some difference of view as to just where the line between the two systems should be drawn. Many European geologists are of the opinion that the Lower Helderberg should be included in the Devonian, but in this country it is generally referred to the Silurian.

At the opening of Devonian times the shore line of North America was approximately as follows. Beginning on the coast of the Arctic Ocean, not far from the mouth of the Mackenzie, it follows a general southeasterly course to the region of Lake

Superior, where it turns westward to an unknown distance, the covering of newer rocks preventing the tracing of the line in that direction. It reappears in northeastern Iowa, whence it turns eastward across Illinois and then sweeps northward enclosing a great bay which extended across Michigan, Ontario, and central New York nearly to the line of the Hudson, where it encounters the western shore of the Appalachian land. The islands over southern Ohio, Kentucky, and Tennessee made by the Cincinnati uplift at the close of the Ordovician, remained much as they had been during the Silurian. The Missouri island, on the other hand, may have been joined to the Wisconsin peninsula and to the land mass of the Southwest. It has been suggested that a north and south ridge of land extended from Wisconsin all the way to South America, dividing the American seas into eastern, interior, and western, just as Europe had been separated into an open northern and a more or less closed southern sea during the Ordovician and Silurian. This suggestion has not yet been definitely confirmed, but it may represent the truth. In the western region extensive islands continued to exist, and were probably somewhat larger than they had been in the Ordovician.

A region separate in its geographical development was the northeastern or Acadian province, which included the enlarged Gulf of St. Lawrence and the narrow channels which still ran southward and southwestward across New England and the maritime provinces of Canada.

In the northeastern bay of the great Interior Sea the records of the Devonian period begin with the formation of a series of thick sandstones, of which the oldest is the *Oriskany*, a calcareous sandstone that is rendered porous on weathering by the removal in solution of the calcareous material and of the fossils with which the rock is crowded. The Oriskany is found over the eastern half of New York and southward along the Appalachian range to Virginia. It is also reported from the folded area of northern Alabama, where it overlaps the Cambrian and Ordovician, indicating a transgression of the sea over the land in that region, for the Silurian is not represented there. Westward the Oriskany extends into

Ontario and recurs in southern Illinois, while in the eastern region it is found in east Canada and as a very thick mass in Maine.

The Oriskany was followed by the grits, or fine conglomerates, of the *Schoharie* stage, which have much the same distribution as the former and are thickest along the line of the Appalachian uplift. Next, a deepening of the water brought about the conditions favourable for the formation of the great *Corniferous* limestone, which has a much wider distribution than the preceding stages and indicates a transgression of the sea over many areas that had been low-lying lands. This limestone extends from the Hudson River across New York to Michigan, and around the islands of the Cincinnati uplift into Indiana, Illinois, Kentucky, Missouri, and Iowa. It is largely made of corals, sometimes as recognizable reefs, a famous example of which is at the Falls of the Ohio, above Louisville. In the eastern province the Corniferous is represented at Gaspé (Quebec) by 2000 feet of sandstones and limestones, and by a coral limestone in northern Vermont.

A change of conditions in the northeastern bay of the Interior Sea checked the formation of limestone, and on a slowly subsiding bottom were laid down great masses of shales and shaly sandstones (which constitute the *Hamilton* series), with a few feet of limestone at the top in many places. The Hamilton has nearly the same distribution as the Corniferous, but thins out much to the west and south, and in the Mississippi valley is represented by limestones. In the eastern province the Hamilton reappears at Gaspé, where it is displayed as a very thick mass of sandstones, and in Nova Scotia and New Brunswick as sandstones and shales.

The Upper Devonian, or *Chemung* series, as formed in the northeastern bay, is an exceedingly thick mass of shales and shoal water, ripple-marked sandstone, reaching in the Appalachian ridges of Pennsylvania a thickness of 8000 feet, but thinning away to the south and west. Indeed, over much of the Mississippi valley the entire Devonian system is represented by a few feet of black shale, a circumstance which it is not easy to explain. In the Upper Devonian sandstone of Pennsylvania are great reservoirs of petroleum and natural gas. Along the eastern shore of the Chemung sea was accumulated an immensely thick sandstone, which was formerly supposed to represent a distinct series and called the *Catskill;* the maximum thickness of this sandstone (7500 feet) occurs in eastern Pennsylvania.

Eastern New York and Pennsylvania were, then, for long ages a slowly sinking marginal sea-bottom, on which, as in a great trough, were accumulated immense masses of shallow-water deposits, with occasional limestones when an increased rate of subsidence deepened the water. During Cambrian and Ordovician times similar conditions had prevailed southward along the line of the future Appalachian range, but in the Silurian and still more in the Devonian, sedimentation became chiefly concentrated in the northern half of the trough, the subsidence of the southern portion having become exceedingly slow and intermittent.

The course of deposition of sediments which occurred during Devonian times in the western portion of the continent was so entirely different from the succession of sedimentation in the eastern half, that it is very difficult to correlate the subdivisions in the two regions, whose seas may have been separated by an unbroken land area. Far to the north, in the Mackenzie River region of Canada and coming down into Manitoba, the Devonian is represented by about 1000 feet of limestones and shales, which appear to belong to the middle and upper part of the system. Another strip of Devonian rocks follows the main range of the Canadian Rocky Mountains, extending southward into Montana. The Front Range in Colorado was apparently a land area, for there the *Carboniferous* strata rest upon the Cambrian and Ordovician, as is also true of central Texas and the Black Hills of South Dakota; but in southwestern Colorado the Devonian reappears. In parts of the Grand Cañon region thin patches of Devonian strata are found lying upon the upper Cambrian sandstones. In the Wasatch Mountains of eastern Utah 2400 feet of quartzites and limestones belong to the Devonian. In Nevada, on the other hand, was a comparatively deep and tranquil marine basin, in which deposition would seem to have gone on uninterruptedly from the Ordovician through the Carboniferous. Of 30,000 feet of Palæozoic rocks, 6000 feet of limestone and 2000 feet of shale are assigned to the Devonian. Beyond the long, narrow strip of land which lay along the western side of the Great Basin, the Devonian reappears in California.

Foreign. — The European Devonian appears under two very different *facies*, or aspects of development; one of these is the "Old Red Sandstone," which was laid down in closed basins having restricted or occasional connection with the sea, and the other is the ordinary marine type. The period began in Europe with an advance of the sea over the land in many places, reaching its maximum extension in the latter part of the period, but beginning to retire before the opening of the Carboniferous. The movement of depression was at first only sufficient to permit the accumulations of shallow-water deposits, which in the Rhine district attain the great thickness of 10,000 feet. The Middle Devonian in the same region is prevailingly a great limestone, and the Upper is made up of limestones and slates. This subsidence removed the barrier which in Ordovician and Silurian times had separated the northern and southern seas, but was accompanied by the formation of closed basins farther to the north. Europe then was largely an open sea with many islands, and where the waters were sufficiently clear and free from terrigenous sediment, coral reefs were extensively formed.

The marine Devonian occurs in the southwest of England, over large areas of Germany, in northwestern and southern France, and on an enormous scale in Russia. During the Silurian the sea had withdrawn almost entirely from Russia west of the Ural Mountains. In the Lower Devonian the sea broke in from the north over Siberia, reaching far into central Asia. In the Middle Devonian a great basin was formed by the depression of central Russia, the sea advancing from the north and the east.

The "Old Red Sandstone" is of particular interest, because, owing to the peculiar circumstances of its formation, it has preserved a record of Devonian land life, which, though fragmentary, is far more complete than anything we possess from the more ancient periods. These strata were laid down in closed basins (sometimes, perhaps, in fresh-water lakes), which had only a restricted communication with the sea. The Old Red is found in south Wales and the adjoining part of England, and, on a much larger scale, in Scotland; also in the Baltic provinces of Russia, where the fossils are mingled with those of the marine Devonian; in Spitzbergen and Greenland the same formation recurs. These sandstones are said to be 10,000 feet thick, but according to some authorities, the lowermost part of them is Silurian. The so-called Catskill of New York is very like the Old Red, and contains similar fossils.

The European Devonian is full of the evidences of volcanic activity, in the shape of great lava flows and tuffs. In central Scotland the volcanic accumulations exceed 6000 feet in thickness.

Besides the Devonian areas already mentioned in Asia, rocks of this system are found in China, the Altai, and in Asia Minor. They recur in northern and southern Africa, being the most ancient Palæozoic rocks yet reported from the latter region. In South America occurred a great transgression of the sea, and Devonian strata form larger areas of the surface than those of any other Palæozoic system. Shallow-water deposits are found in Bolivia, over large parts of Brazil, especially the basin of the Amazon, and in the Falkland Islands. The Bolivian Devonian, which belongs to the lower and middle parts of the system, contains a very similar fauna to that of North America and connects the latter with Brazil, the Falkland Islands, and south Africa.

DEVONIAN LIFE

The life of the Devonian is, in its larger outlines, very like that of the Silurian, but with many significant differences, which are due, on the one hand, to the dying out of several of the older groups of animals, and, on the other, to the great expansion of forms which in the Silurian had played but a subordinate rôle.

Plants. — The fossils show that in Devonian times the land was already clothed with a varied, rich, and luxuriant vegetation of the same general type as that whose scanty traces are found in Silurian strata. All the higher Cryptogams are represented, and by large, tree-like forms, as well as by small herbaceous plants. The bulk of the flora is composed of *Ferns*, *Lycopods* (especially the great tree-like *Lepidodendrids*), and *Equisetaceæ*. *Rhizocarps*, which are now almost extinct, were then abundant. Besides these Cryptogams, we find representatives of the lower kinds of flowering plants in the *Gymnosperms*, including the Cycads and perhaps the Conifers, which presumably grew upon the higher lands. We shall meet this same flora in richer and more varied display in the Carboniferous period.

Foraminifera and **Sponges** are not conspicuous elements of the Devonian fauna.

Cœlenterata. — The Graptolites, which were so abundant in the Ordovician and had become much less common in the Silurian, are now almost extinct, only a few simple species occurring in the Lower Devonian. The *Corals*, on the contrary, expand and multiply enormously both in numbers and in size. Most of the Silurian genera persist (though the chain-coral *Halysites* has become extinct), and many new forms are added. *Heliophyllum* (Pl. IV, Fig. 1) is an example of the solitary corals, and *Phillipsastræa* and *Acervularia* (IV, 2) of the reef-builders.

Echinodermata. — The Cystids have become much rarer than before, and are on the point of extinction; the Blastoids are still in the background, and the Echinoids have not yet become common; but the Crinoids and Star-fishes have greatly increased in number and variety. Important genera of the former group are *Cupressocrinus*, *Platycrinus*, *Actinocrinus*, etc. The multitude of the crinoids contributed largely to the building up of the calcareous sea-bottom on which they flourished.

Arthropoda. — The Trilobites had already begun to decline in the Silurian, while in the Devonian the decline had become very much more marked, though they were still far from rare. New species of Silurian genera, like *Phacops* (IV, 12), *Homalonotus* (IV, 11), *Lichas*, *Acidaspis*, etc., are the commonest. A character-

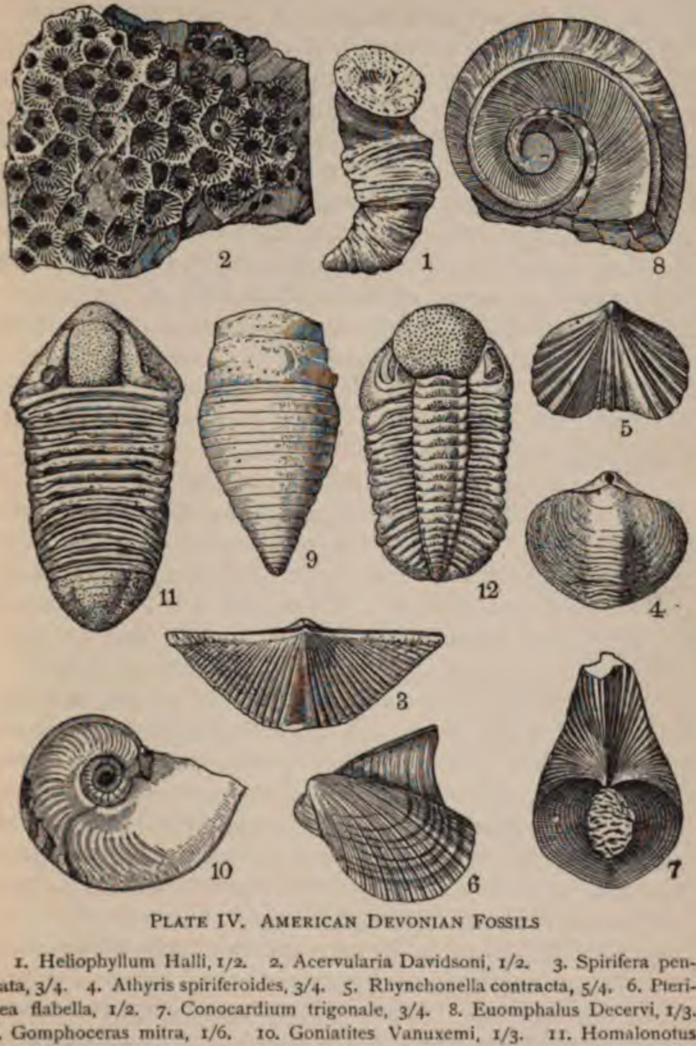


PLATE IV. AMERICAN DEVONIAN FOSSILS

1. Heliophyllum Halli, 1/2. 2. Acervularia Davidsoni, 1/2. 3. Spirifera pennata, 3/4. 4. Athyris spiriferoides, 3/4. 5. Rhynchonella contracta, 5/4. 6. Pterinea flabella, 1/2. 7. Conocardium trigonale, 3/4. 8. Euomphalus Decervi, 1/3. 9. Gomphoceras mitra, 1/6. 10. Goniatites Vanuxemi, 1/3. 11. Homalonotus Dekayi, 1/3. 12. Phacops rana, 1/2. (Figs. 1, 2 after Rominger. 3–7, 9–12 after Hall. 8 after Meek.)

istic of the Devonian Trilobites is the extraordinary development of spines which many display on the head- and tail-shields.

The other Crustacea make notable progress in this period. The first of the *Isopoda* and of the long-tailed *Decapoda* (lobster-like forms) make their appearance in the Devonian. The *Eurypterids* now attain their culmination in size, being actually gigantic for Crustacea, and some of them are as much as six feet long. The genera (*Eurypterus*, *Stylonurus*, and *Pterygotus*) are the same as in the Silurian. *Insects*, though still rare as fossils, are very much commoner than in the Silurian; they represent both Orthopters and Neuropters, which are among the primitive groups.

Brachiopoda. — As in the Silurian, Brachiopods continue to be the most abundant fossils, both in species and individuals, in the Devonian, from which more than 1000 species have been described. Many Silurian genera have died out, and others, like *Orthis* and *Strophomena*, have become much less common; and of others again, like *Chonetes* and *Productus*, the species are more numerous. The most characteristic shells are those belonging to the genera *Spirifera*, especially the very broad "winged" species, (IV, 3), *Rhynchonella* (IV, 5), *Athyris* (IV, 4), and those belonging to the still existing family *Terebratulidæ*, of which *Rensellaria* and *Stringocephalus* are Devonian genera.

Mollusca. — Bivalves and Gastropods are much as in the Silurian: examples of the former are *Pterinea* (IV, 6) and *Conocardium* (IV, 7), while large species of the Gastropod *Euomphalus* (IV, 8) are characteristic. The Cephalopods have been revolutionized; the wealth of Nautiloid shells which we found in the Silurian has been much diminished, though *Orthoceras*, *Phragmoceras*, *Gomphoceras* (IV, 9), and *Cyrtoceras* still persist, but with fewer species than before, while many other genera have disappeared. More significant is the first appearance of the Ammonoid division of the Tetrabranchiate Cephalopods, a group of shells which was destined to attain extraordinary development in the Mesozoic era. The Ammonoids are distinguished by the complexity of the "sutures," or lines made by the junction of the septa with the outer wall of the shell. In the Devonian Ammonoids, of which *Goniatites* (IV, 10; V, 11) is the common form, the sutures are much less complex than in the Mesozoic shells. Another member of the group which is far more abundant in Europe than in America is *Clymenia*, the only Ammonoid in which the siphuncle is on the inner side of the spiral. *Bactrites* has a straight shell, like that of *Orthoceras*, but with the complex sutures which show it to be an Ammonoid.

Vertebrata. — One of the most characteristic features of Devonian life is the great development of the aquatic Vertebrates, which is so striking that the period is often called the "Age of Fishes." So numerous and so finely preserved are these fossils that a satisfactory account may be given of the structure and systematic position of many of the genera. This great assemblage of fishes and fish-like forms, it should be remembered, is not something entirely new in the earth's history, but the wonderful expansion of types which during the Ordovician and Silurian had remained very much in the background.

Of the Devonian Vertebrates none are more peculiar and characteristic than the *Ostracoderms*, which, though generally called fishes, really belong to a type much below the true fishes and more nearly allied to the Lampreys, being devoid of jaws and of paired fins. The head and more or less of the body are sheathed in heavy plates of bone, and the remainder of the body and the tail are covered with scales. No trace of the internal skeleton is preserved, and it evidently was not ossified. The genus *Cephalaspis* of this group is curiously like a Trilobite in appearance, though, of course, the resemblance is entirely superficial. The head-shield is formed of a single great plate of bone, shaped like a saddler's knife, with rounded front edge and with the hinder angles drawn out into spines; the eyes are on the top of the head and very close together. The body is covered with large, angular plates of bone, arranged in rows; a small median dorsal fin and a larger triangular tail-fin make up the locomotor apparatus.

Pteraspis has a bony plate over the snout, a large shield on the back and another on the belly, with rhomboidal scales covering the rest of the body.

A most extraordinary-looking creature is *Pterichthys* (Fig. 140), in which the head and most of the body are encased in heavy plates, the remainder in overlapping scale-like bones ; the eyes are even closer together than in *Cephalaspis*. Dorsal and tail-fins are present and what appear to be pectoral fins. The pair of appendages referred to doubtless acted as fins, but they are not comparable to the paired fins of the true fishes, being merely jointed extensions of the head-shield. These three genera, *Cephalaspis, Pteraspis*, and *Pterichthys*, have been selected as types of the Ostracoderms, each one of which has several allies, differing from it in one or other particular.

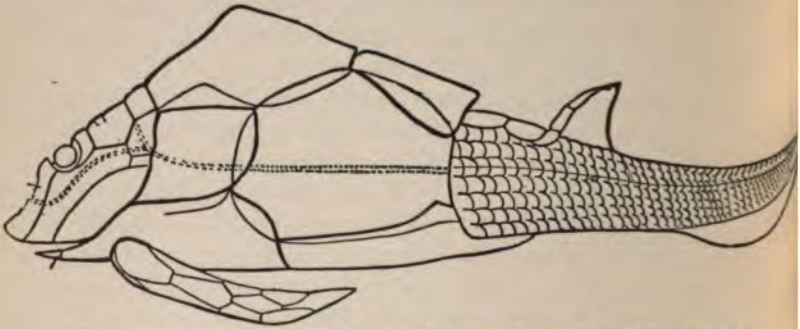


FIG. 140.— Pterichthys testudinarius. (From Dean, after Smith Woodward.)

Of the true *Fishes* there is great variety in the Devonian. The *Selachians* are well represented, one of which is *Cladoselache* (Fig. 141), a small shark, from two to six feet in length, and the most primitive known member of the group. The *Dipnoi*, or Lung Fishes, were important elements of the Devonian fish fauna.

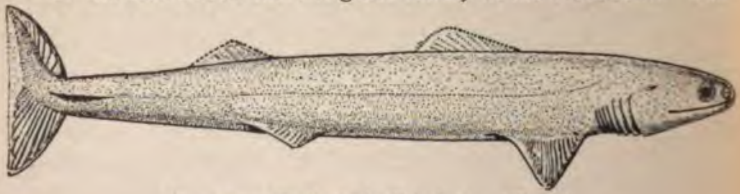


FIG. 141.— Cladoselache Fyleri, 1/5. (Dean.)

Dipterus (Fig. 142), an example of this group, is very like the modern lung fishes, which have dwindled to three genera, one in South America, one in Africa, and one in Australia. A remarkable series of fishes, the *Arthrodira*, are regarded, though with some doubt, as a division of the lung fishes. One of the best-known members of this group is the European genus *Coccosteus* (Fig. 143), in which the head, back, and belly are covered with bony plates, but the rest of the body is naked. This bony armour gives the fish something of the appearance of the Ostracoderms, with which group it is often, though erroneously, classified. The backbone is represented by an unsegmented rod (the notochord, *N*, Fig. 143), to which arches of bone are attached (*N*, *H*, Fig. 143). Paired ventral fins were present, but pectorals have not been found. The jaws were provided with teeth, which fuse into plates. In the uppermost Devonian of Ohio are found some huge fishes allied to *Coccosteus*, but much larger and more formidable. The most important of these are *Dinichthys* and *Titanichthys*, the latter attaining a length of 25 feet.

A higher type of Devonian fish is that of the *Crossopterygii*, an

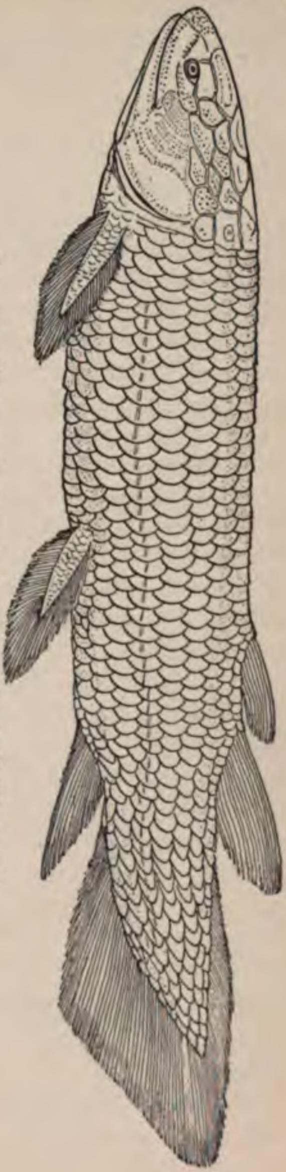


FIG. 142. — Dipterus valenciennesi, 1/3. (Dean, after Smith Woodward.)

ancient group of which but two representatives remain at present, both of them African. These fishes, like the Dipnoans, have "lobate" paired fins (see Fig. 144), *i.e.* the part of the fin belonging to the internal skeleton is large and covered with scales, forming a lobe to which the fin-rays are attached. Most of the Devonian members of the group have massive rhomboidal scales, but in others, like *Holoptychius*, the scales are thinner, rounded, and overlapping.

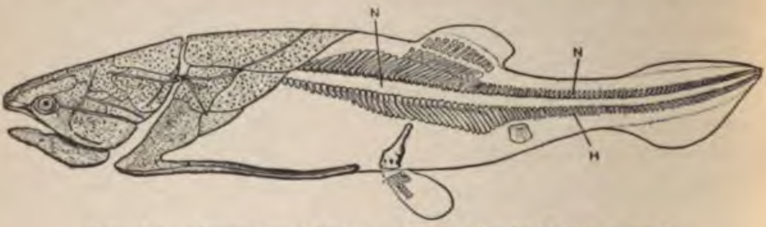


FIG. 143.—Coccosteus decipiens. (Dean, after Smith Woodward.)

The most advanced fishes of the period are the Ganoid members of the Actinopterygians, which from the Devonian until nearly the end of the Mesozoic era continue to be the dominant type of fishes. Nearly all of them have thick, shining scales of rhomboidal shape.

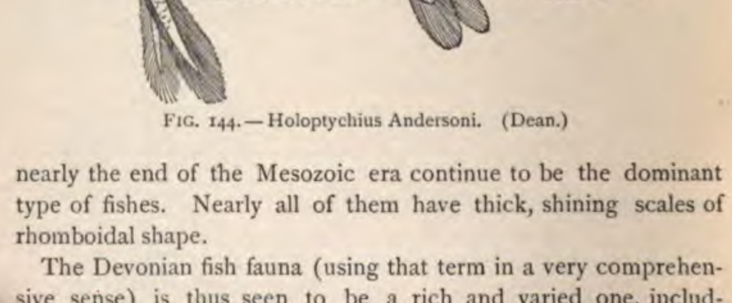


FIG. 144.—Holoptychius Andersoni. (Dean.)

The Devonian fish fauna (using that term in a very comprehensive sense) is thus seen to be a rich and varied one, including Ostracoderms, Sharks, Lung Fishes, Crossopterygians and Actinopterygians, each with many representatives and mostly of very curious and bizarre forms. While thus varied and plentiful, this assemblage differs from the modern fish fauna in the primitive character of the groups which are represented, and in the entire absence of the Bony Fishes (*Teleosts*), which now make up the vast majority of fishes, both fresh-water and marine.

Amphibia. — Certain footprints which have been recently reported from the Upper Devonian of Pennsylvania, show that the Amphibia, the lowest of air-breathing vertebrates, had already begun their career.

CHAPTER XXVI

THE CARBONIFEROUS PERIOD

THE name *Carboniferous* was given in the early part of the present century, when it was supposed that every geological system was characterized by the presence of some peculiar kind of rock. We now know that this conception is erroneous and that workable coal seams have been formed in all the periods since the Carboniferous. It still remains true, however, that the latter contains much the most important share of the world's supply of mineral fuel, upon which the whole fabric of modern industrial civilization is founded. The great economic importance of the coal measures has caused them to be most carefully surveyed in all civilized lands, a process greatly assisted by the innumerable shafts and borings which penetrate these rocks. One result of this gigantic work is, that the history and life of the Carboniferous are better known than those of any other Palæozoic period, though our knowledge is still very far from complete.

The Carboniferous rocks are displayed in very different aspects or facies in the various parts of the continent and even in contiguous regions. New York no longer gives the standard scale, for that state has very little that is newer than the Devonian. For the eastern part of the country the sequence of strata in Pennsylvania serves as the scale of reference, while a very different one is needed for the Mississippi valley. In the Rocky Mountain region, again, the character of deposition deviated markedly from what occurred in the East, and all over the far West the Carboniferous is entirely marine, without coal. Even in this region, however, the distinction between the Lower and Upper Carboniferous may be drawn. The following table, modified from Dana's, gives the succession in Pennsylvania and the middle West, Illinois, Missouri, Iowa, etc.

	PENNSYLVANIA		MISSISSIPPI VALLEY	
Upper Carboniferous Series.	4. Upper Productive Stage.		2. Coal Measures.	
	3. Lower Barren Stage.			
	2. Lower Productive Stage.			
	1. Millstone Grit Stage.		1. Millstone Grit.	
Lower Carboniferous Series.	2. Mauch Chunk Stage.	Mississippian.	4. Chester Stage.	
			3. St. Louis Stage.	
			2. Osage Stage.	Warsaw Substage. Keokuk Substage. Burlington Substage.
	1. Pocono Stage.			
			1. Kinderhook Stage.	

DISTRIBUTION AND SEQUENCE OF CARBONIFEROUS ROCKS

American. — In many parts of North America the Devonian was followed so quietly by the Carboniferous, that it is very difficult to draw the line between them, but in other regions notable geographical changes occurred. In the Acadian province, as at Gaspé, and in Nova Scotia, New Brunswick, and Maine, there was a time of upheaval and erosion toward the end of the Devonian, followed by a renewed depression, in consequence of which there is an unconformity between the two systems. When the Carboniferous period began, most of New England, eastern Canada, and Newfoundland was land, but the Gulf of St. Lawrence was still much larger than at present, covering western Newfoundland, most of New Brunswick, and part of Nova Scotia, and sending two long, narrow arms southwestward as far as Massachusetts and Rhode Island.

In the Interior Continental Sea wide-spread changes occurred, but they were accomplished by slow oscillations of level, not accompanied by violent disturbances. In the Rocky Mountain region, there took place a great deepening and transgression of the sea, and many of the land areas, the outline of which is still very vaguely known, became extensively submerged. In consequence of this transgression, the Carboniferous strata rest unconformably, or in apparent conformity, upon Cambrian, Ordovician, and Silurian rocks. From the Rocky Mountains westward Carboniferous rocks are much more widely extended than those of any other Palæozoic system, but they cannot yet be compared in detail with those of the East. In the central portion of the Interior Sea there was likewise a deepening and extension of the waters, forming clear seas, in which marine organisms flourished luxuriantly, and great bodies of limestone were formed over areas where the Devonian is very thin or altogether absent. The northern islands of the Cincinnati uplift became joined to the northern land, forming a long, narrow peninsula, while a strip was added along the western side of the Appalachian land. The northeastern part of the Interior Sea was thus divided into two bays, the larger one covering nearly all of Pennsylvania, the eastern part of Ohio and Kentucky, and West Virginia, the other occupying the southern peninsula of Michigan and communicating with the first by a narrow strait. So long as marine conditions lasted in these bays, the rocks laid down in them were nearly all fragmental, conglomerates, sandstones, and shales (though with occasional layers of limestone), and it is very difficult to correlate them with the thick masses of limestone accumulated in the clearer and deeper waters farther west.

The Carboniferous strata are divisible into two great series, the Upper Carboniferous or coal measures above and the Lower Carboniferous (often called Subcarboniferous) below, though it must not be supposed that the formation of coal began simultaneously in all the areas, for, as a matter of fact, we know that it did not. In the Acadian province (Nova Scotia and New Brunswick) the lower part of the Carboniferous system is made up of thick masses of sandstone and conglomerate with overlying limestones, the latter with inclusions of gypsum, which indicate the occasional formation of closed lagoons. The thickness of these beds together amounts to 6000 feet.

In Pennsylvania the lower members of the system are the *Pocono* sandstone and the *Mauch Chunk* shales, which together have a maximum thickness of 4000 feet. The hard Pocono sandstone forms the summit of the plateau of that name and of many of the Allegheny ridges. Westward and southward the sandstone and shales thin away quickly, showing that their great thickness at the northeast was due to the rapid deposition of sediment upon the sinking bottom of that part of the bay. In Ohio the *Waverly* beds, representing the same time, are a mass of shales 700 feet thick, with some sandstone and limestone at the top. In the Michigan bay were laid down the *Marshall* beds, sandstones, grits, and shales below, followed by shales with some limestone and gypsum, which point to a temporary closing of the straits and the conversion of the bay into a salt lake. The barrier was, however, removed and the bay deepened, allowing the formation of a marine limestone.

Westward from the bays the deepening of the open Interior Sea was followed by the accumulation of the great masses of limestone which constitute the *Mississippian* series, and which were formed from a most luxuriant growth of corals, brachiopods, and crinoids. Six different stages and substages (see table) may be distinguished in these limestones, and evidences of shifting coast lines are not wanting. Thus, the *Kinderhook* extends farther north and west than the *Osage*, while the *St. Louis* represents a renewed transgression of the sea northward. The Mississippian limestones have a thickness of 1200 to 1500 feet in southern Illinois, thinning out northward, where the coal measures overlap them and rest upon the Devonian. These limestones extend over southern Indiana, Illinois, Iowa, Missouri, Kentucky, Tennessee, and southwestward to Arkansas and Texas.

Over the eastern part of the Interior Sea, where there had been but scanty deposition during Devonian times, a sinking sea-bottom and deeper water in the Lower Carboniferous were favourable to the formation of limestones. In West Virginia occur nearly 1300 feet of sandstone and shale, with 800 feet of limestone. In Virginia are 2000 feet of limestones, sandstones, and shales, with many thin seams of coal, some of them workable. The formation of peat bogs thus commenced in this region, as also in Nova Scotia, before it did in Pennsylvania, and to distinguish them, these lower coal-bearing beds are often called the *False Coal Measures*.

At the close of Lower Carboniferous time occurred wide-spread changes of level, which are reflected in the character of the rocks, and in erosion of the lower strata, forming depressions and basins in which peat bogs gathered. In the first instance, the change consisted in a very extensive but slow elevation of the sea-bottom, raising it in places into land. The coal measures which sometimes lie unconformably upon the Lower Carboniferous, were inaugurated by a transgression of the sea, beyond the areas occupied by the Lower Carboniferous waters. The thick sheets of conglomerate and coarse sandstones (*Millstone Grit*) at the base of the coal measures were laid down in the encroaching sea. Contemporaneous erosion (see p. 272) and local unconformities occur within the coal measures. The movement resulted in making a vast area of low-lying lands, which were raised very little above sea-level and upon which great swamps and marshes were established, where vegetation flourished in tropical luxuriance. A very slow subsidence, often intermittent, allowed great thicknesses of material to accumulate, but frequently a more rapid sinking brought in the sea, or bodies of fresh water over the bogs, killing the trees which grew there. We cannot yet determine how far the different coal regions represent separate basins, and how far their separation is due to the subsequent removal of connecting strata, but even in connected areas we find great differences in the nature and thickness of the beds. This indicates that oscillations of level of different amounts took place in particular parts of the same basin. Thus, in one portion may occur a coal seam of great thickness, divided into two or more layers by exceedingly thin "partings" of shale. As we trace the coal seam in the proper direction, the partings gradually grow thicker, until, perhaps, they become strata, that intervene between very distinct and quite widely separated coal seams, each of which is continuous with the corresponding portion of the thick seam. The meaning of such a structure is, that while one part of the bog subsided very slowly, permitting the almost uninterrupted accumulation of vegetable matter, other portions sank more rapidly and were inundated with water, which deposited mechanical sediments on the surface of the submerged bog.

Hardly more than 2% of the thickness of the coal measures consists of workable coal. The strata are mostly sandstones, shales, clays, and in some regions limestones, interstratified with numerous seams of coal of very varied thicknesses. This alternation of coal with mechanical deposits does not necessarily, or even probably, imply oft-repeated oscillations of level, but may be explained by assuming a general, slow, but intermittent subsidence. After each submergence, we may suppose, the movement was nearly or quite arrested, and the shallow water was filled up with sediment, until a bog could again be formed. Doubtless, movements of elevation also occurred at times, but the general movement was downward. In the Nova Scotia field are 76 distinct coal seams, each of which implies the formation of a separate bog. Beneath most coal seams occurs what miners call the "seat-stone" or "underclay," which is ordinarily a fire-clay, or it may be siliceous, but is always evidently an ancient soil. The underclay is filled with fossil roots, from which often rise the stumps of trees that penetrate the coal seam, or may even extend many feet above it. The rock which lies on a coal seam is usually a shale, stained black by organic matter, but may be a sandstone or even a limestone, according to the depth of water over the submerged bog.

That coal is of vegetable origin is no longer questioned. Such a mode of origin is directly proven by microscopical examination, which shows that even the hardest anthracite is a mass of carbonized but determinable vegetable fibres. On the other hand, there has been much difference of opinion concerning the way in which such immense masses of vegetable matter were brought together. Much the most probable view is, that the coal was formed in position in great peat bogs, added to, no doubt, by more or less drifted material. The evidence for this view is to be found: (1) in the great extent and uniform thickness and purity of many coal seams, which we cannot account for in any other way. Had the vegetable matter been largely drifted together, it must have been contaminated with sediment and could not have been spread out so evenly over great areas. This objection to the "driftwood theory" becomes all the stronger when it is remembered that the process of converting vegetable matter into coal greatly reduces its bulk, a given thickness of coal representing only about 7% of the original thickness of vegetable substance. Thus a 20-foot seam of coal implies the accumulation of nearly 300 feet of plants, and it is highly improbable that such a mass could have been evenly spread as drift over hundreds (or even thousands) of square miles, without a large admixture of mud or sand. (2) The very general presence of the underclay beneath coal seams points to the same conclusion. An underclay, as we have seen, is an ancient soil, and is of just the same character as that which we find under such modern peat bogs as the Great Dismal Swamp (see pp. 134–135).

The subsidence of the bogs and the deposition of sediments upon them gradually built up the great series of strata which are called the coal measures. The peat was thus subjected to the steadily increasing pressure of the overlying masses, which greatly aided in the transformation of the vegetable accumulations into coal. Where the coal measures have been folded, the still greater pressure, aided by heat, and perhaps by steam, has resulted in the formation of anthracite. The greater number of the Carboniferous bogs appear to have been covered by fresh water, though some were coast swamps, extending out into brackish or even salt water.

The workable coal fields of North America, belonging to the Carboniferous system, are found in several distinct areas, some of which were doubtless separate basins of accumulation, while others have become disconnected by denudation.

(1) In the Acadian province the coal measures occur in the island of Cape Breton, Nova Scotia, and New Brunswick; in Nova Scotia they are of immense thickness, 7000 feet, with 6000 feet of underlying conglomerate. A second basin of this province is near Worcester (Mass.), and a third extends through Rhode Island into southeastern Massachusetts. The latter basins are metamorphic and yield a very hard anthracite.

(2) The great Appalachian field has an area of more than 50,000 square miles. It covers most of central and western Pennsylvania, eastern Ohio, western Maryland and Virginia, and

West Virginia, eastern Kentucky and Tennessee, to northern Alabama. In this field the measures are thinner than in Nova Scotia; the beds are thickest along the Appalachian shore line, about 4000 feet in western Pennsylvania and 3000 in Alabama, thinning much to the westward.

(3) In Michigan the measures are only about 300 feet thick and were doubtless laid down in an isolated basin.

(4) The Indiana-Illinois field, which extends into Kentucky, is from 600 to 1000 feet thick.

(5) The Iowa-Missouri field extends southward around the Palæozoic island of southern Missouri into Arkansas and Texas. In Arkansas the Carboniferous system, as a whole, attains a greater thickness than anywhere else in North America.

The two latter fields are separated by a very narrow interval, and almost certainly were once continuous; the Indiana-Illinois field was probably also connected with the Appalachian area across western Kentucky and Tennessee.

As the coal measures are traced westward into Kansas, Nebraska, and adjoining states, we find them dipping beneath strata of a very much later date. When they once more return to the surface, as in the Rocky Mountain region, they appear under an entirely new aspect, being here altogether marine and containing no coal. In Arizona and Utah a very large area is covered by Carboniferous limestones and sandstones, and they form much of the thickness of the lofty plateaus through which the Colorado has cut its cañons. Carboniferous beds occur around the Colorado island, in the Black Hills, westward in the Uinta and Wasatch Mountains, and over eastern Nevada. The thickness of the beds increases from the Rocky Mountains westward, reaching 13,000 feet of limestones and quartzites, for the whole Carboniferous system, in Utah and Nevada, where deposition seems to have gone on uninterruptedly from the Cambrian. In western Nevada was the Pacific shore, beyond which Carboniferous beds reappear in California and British Columbia, extending over the interior plateau of the latter region as far as 55° N. lat., and perhaps much farther. Many Arctic islands have Carboniferous strata.

Thus, in Carboniferous times we observe a striking difference between the development of the eastern and western halves of the continent. At first, there was a deepening and extensive transgression of the sea. This was followed in the eastern interior region by the upheaval of vast areas into low, swampy flats. In the West the sea held sway throughout the period, and the conditions for the accumulation of coal were not brought about. This was done, as we shall learn, at a far later time. In the East there were numerous oscillations of level, as is shown by the character of the strata, though the movements were very slow and gentle; but in parts of the West, as around the Colorado island, there were some disturbances, and unconformities between the Upper and Lower Carboniferous beds have been detected. No volcanic rocks have been found in this system, East or West.

Foreign. — In Europe the Carboniferous system is developed in a very interesting way. In the western and central parts of the continent (and in Great Britain) the succession of strata is very similar to that of the eastern half of North America, while in Russia it has more analogy with the western half of our continent. The changes of level which opened the period converted much of the Devonian sea-bed into land, but at the same time the sea broke in over many of the closed basins in which the Old Red Sandstone had been laid down. From the west of Ireland to central Germany, a distance of 750 miles, stretched a clear sea, free from terrigenous sediments, in which flourished an incredible number of corals, crinoids, and other calcareous organisms. From their remains was constructed an immense mass of limestone, having a thickness of 6000 feet in the northwest of England and of 2500 feet in Belgium. Above this great "mountain limestone," as it is called in England, come the coal measures. In Scotland the limestone is replaced by shore and shallow-water formations, such as sandstones, with some coal. In the southwest of England and east of the Rhine in Germany, the Lower Carboniferous is represented, not by a limestone, but by a series of sandstones and slates, called the *Culm*, with the coal measures above. In Russia the order of succession is reversed, the productive coal beds being below and the great bulk of the limestone above. This younger Carboniferous limestone is often called the *Fusulina limestone*, being principally composed of shells belonging to that genus of Foraminifera (Pl. VI, Fig. 1). Great areas of southern and eastern Asia are covered by this limestone, which is also largely developed in western North America, extending as far east as Illinois. In southern Europe, Spain, the south of France, the Alps, and the Balkan peninsula, the Lower Carboniferous is partly limestone and partly culm, while the Upper is largely made up of the Fusulina limestone. In the Arctic Sea, Nova Zembla, Spitzbergen, and Greenland have Upper Carboniferous limestones.

The following table, from Kayser, displays the relations of the Carboniferous beds in eastern and western Europe.

	Littoral and Lacustrine Facies	Marine Facies	
Upper Carboniferous.	Productive Coal Measures (Western Europe).	Younger Carboniferous or Fusulina Limestone (Russia, etc.).	
Lower Carboniferous.	Productive Coal Measures (Russia, etc.).	Lower Carboniferous Limestone (Western Europe).	Culm (Germany).

In western Europe the Carboniferous period did not run such a tranquil course as in North America, but was broken by disturbances, of which the greatest were at the close of the Lower Carboniferous epoch, when the rocks were folded and upturned over extensive regions. These movements were accompanied and followed by volcanic outbursts, especially in Scotland, France, and Germany, and great eruptions occurred in China at the end of the period.

In Asia are large areas of Lower Carboniferous limestone and culm, and of the Upper Carboniferous both Fusulina limestone and productive coal measures. China is one of the richest countries in the world in supplies of coal.

Carboniferous limestones are found in Morocco, the Sahara, and in southern Africa.

The Carboniferous limestones and coal measures are extensively developed in the colonies of New South Wales and Tasmania. In South America the Carboniferous is not nearly so extensive as the Devonian; the Lower Carboniferous is principally composed of sandstones, while the upper series, containing the Fusulina limestone, has been found in Peru, Bolivia, and Brazil.

CARBONIFEROUS LIFE

The life of this period is thoroughly Palæozoic and continues along the lines already marked out in the Devonian, but there are some notable changes and advances which look toward the Mesozoic order of things.

Plants. — The Carboniferous vegetation is of very much the same character as that of the Devonian, but owing to the peculiar physical geography of the times, the plants were preserved as fossils in a much more complete state and in vastly larger numbers. The flora is composed entirely of the higher Cryptogams and the Gymnosperms, no plant with conspicuous flowers having come into existence, so far as we yet know. By far the most abundant of Carboniferous plants are the *Ferns*, which flourished in multitudes of species and individuals, both as tall trees and as lowly, herbaceous plants. Many of these ferns cannot yet be compared with modern ones, because the organs necessary for trustworthy classification have not been recovered, and such are named in accordance with the venation of the leaves. In other cases the comparison with existing ferns may be definitely made, and these remains show that many of the modern families (*Marattiaceæ*, *Ophioglossaceæ*, etc.) had representatives in the Carboniferous forests and swamps.

Even more conspicuous, though much less varied, were the *Lycopods*, the remarkable character of which has been elucidated by the long-continued and laborious efforts of many investigators. While the ferns have remained an important group of plants to

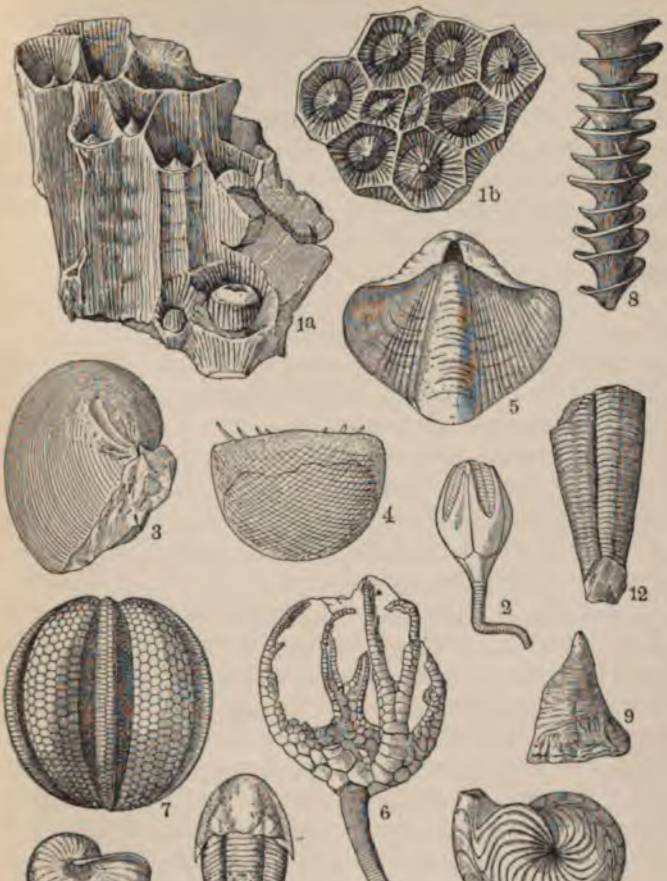


Plate V. American Lower Carboniferous Fossils

1. Lithostrotion canadense, 3/4. 2. Pentremites pyriformis. 3. Productus burlingtonensis, 1/2. 4. Chonetes Fischeri. 5. Spirifera plena, 1/2. 6. Onychocrinus exsculptus, 1/2. 7. Melonites multipora, 1/2. 8. Archimedes Wortheni, 1/2. 9. Platyceras infundibulum, 3/4. 10. Bellerophon sublævis. 11. Goniatites ixion, 1/3. 12. Conularia missouriensis, 1/2. 13. Phillipsia bufo, 3/4. (Figs. 1–6, 8, 10, 11 after Hall. Fig. 7 after Roemer. Fig. 12 after White. Figs. 9, 13 after Meek and Worthen.)

the present time, the Lycopods have dwindled to a few insignificant herbaceous forms, but in Carboniferous times they were the abundant and conspicuous forest trees, at least of the swampy lowlands. One of the most characteristic of these trees was *Lepidodendron* (Pl. VI, Fig. 12), of which many species have been found in the coal measures. These great club-mosses had trunks of 2 or 3 feet in diameter and 50 to 75 feet high, which possessed the remarkable quality, for a Cryptogam, of an annual growth in thickness. At a considerable height above the ground the trunk divides into two main branches, each of these again into two, and so on (dichotomous division). The younger parts of the tree are covered with long, narrow, stiff, and pointed leaves, while the older parts are without leaves, which have dropped off, making conspicuous scars, arranged in spiral lines around the stem. At the ends of the twigs in some species, or on the sides of the trunk and larger branches, in others, are found the spore-bearing bodies, which have much the appearance of pine-cones. The stem was, to a large extent, filled with loose tissue and had only a relatively small amount of wood.

Another very characteristic and abundant tree is *Sigillaria;* it is closely allied to Lepidodendron, but has a very different appearance. The trunk is quite short and thick, rarely branching, and with a pointed or rounded tip, much as in the great Cactus; the leaves are similar to those of Lepidodendron, but are arranged in vertical rows. Sigillaria also possessed the power of annual increase in diameter. Both Lepidodendron and Sigillaria are provided with branching rhizomes, or underground stems, which carry finger-like appendages inserted into pits. Before the nature of these rhizomes was understood, they were regarded as distinct plants and named *Stigmaria.*

A third group of Cryptogams, the *Equisetaceæ*, or Horsetails, were of great importance in the Carboniferous forests. The *Calamites* were decidedly superior to the existing horsetails, not only in size, but in many features of organization as well. These plants had tall, slender stems divided by transverse joints, with a soft inner pith, surrounded by a ring of woody tissue, which grew annually in thickness. The shape and arrangement of the leaves differ much in the various genera; for example, they are needle-like in *Astrophyllites*, while in *Annularia* they are broad and at the base united into a ring around the stem. The shape, size, and position of the spore-bearing organs likewise differ in the different genera, but often resemble those of the modern horsetails. The base of the stem tapers abruptly, and is either connected with a horizontal rhizome or gives off a bundle of roots. Fragments of calamite stems are among the commonest fossils of the coal measures (Pl. VI, Fig. 13).

The *Flowering Plants* are still represented only by the Gymnosperms, of which *Cordaites* is a common example. This plant had a slender trunk, branching above into a pyramidal shape and having long, broad, pointed leaves like those of certain lilies in form. The trunk had a large, soft, inner pith. Cordaites is referred to the Cycad division of the Gymnosperms, but has certain resemblances to the Conifers, which were probably also present in the Carboniferous vegetation.

The Carboniferous flora is merely the Devonian flora somewhat advanced and diversified, but the forests were of the same gloomy, monotonous character as before. The wide distribution and uniform character of this flora are very remarkable; we find the same or nearly allied species of plants spread over North America, Europe (even in the polar lands, like Spitzbergen and Nova Zembla), Siberia, China, the Sinai peninsula, Brazil, Australia, and Tasmania. This uniformity of vegetation indicates a corresponding similarity of climate over nearly the whole world, for no trace of climatic zones can be found.

Foraminifera. — For the first time these animals assume considerable importance in the earth's economy. Many genera which are still living had representatives in the Carboniferous seas, but the most conspicuous and abundant is the extinct *Fusulina* (Pl. VI, Fig. 1), a very large kind, with shells resembling grains of wheat in size and shape. This genus is especially developed in the Upper Carboniferous.

Sponges are common, though rarely found in good preservation.

Cœlenterata. — Corals were abundant, and contributed largely to the limestones; the genus *Lithostrotion* (Pl. V, Fig. 1), which is peculiar to this period, plays a very prominent part. *Lophophyllum* (Pl. VI, Fig. 14) is found in the Upper Carboniferous.

Echinodermata make up an exceedingly important part of the Carboniferous marine fauna. The *Cystids* have disappeared, but the *Blastoids* have developed in great numbers and are highly characteristic of the Carboniferous limestones. As the group is entirely extinct and does not pass beyond the Carboniferous system, its structure has much that is problematical about it. The delicate, symmetrical body or *calyx* (Pl. V, Fig. 2), which is carried on a short stem, is composed of a small, definite number of plates, and has five "pseudo-ambulacral" areas, which look much like the ambulacra of a sea-urchin, but really are not at all comparable to them. In exceptionally well preserved specimens numbers of delicate pinnules are attached to these areas. The most abundant genera are *Pentremites* (V, 2) and *Granatocrinus*.

All other Echinoderms of the Carboniferous seas were utterly insignificant as compared with the *Crinoids*, which reach their culmination of development in this period: more than 600 species have been described from the Carboniferous limestones of North America alone. Certain localities, such as Burlington (Ia.) and Crawfordsville (Ind.), are famous for the vast numbers and exquisite preservation of their fossil sea-lilies. The crinoid remains occur in such multitudes that in many places the limestones are principally composed of them; in such places they must have covered the sea-bottom like miniature forests. All the Carboniferous Crinoids, like those of the earlier periods, belong to the

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EXPLANATION OF PLATE VI, p. 423. 1. Fusulina ventricosa, 2/1. (Meek.) 2. Æsiocrinus magnificus, 1/2. 3. Spirifera camerata, 2/3. (Hall.) 4. Productus punctatus, 1/2. (White.) 5. Euomphalus subrugosus. (Meek.) 6. Pleurotomaria tabulata, 1/2. (White.) 7. Loxonema semicostata. (Meek.) 8. Aviculopecten neglectus. (Meek.) 9. Allorisma subcuneatum, 1/2. (White.) 10. Sphenophyllum Schlotheimi, 1/2. 11. Pecopteris orcopteridis, 1/2. 12. Lepidodendron cuneatum, fragment of bark, 1/2. (Rogers.) 13. Calamites Suckowi, 1/2. (Lesquereux.) 14. Lophophyllum proliferum. (Meek.)

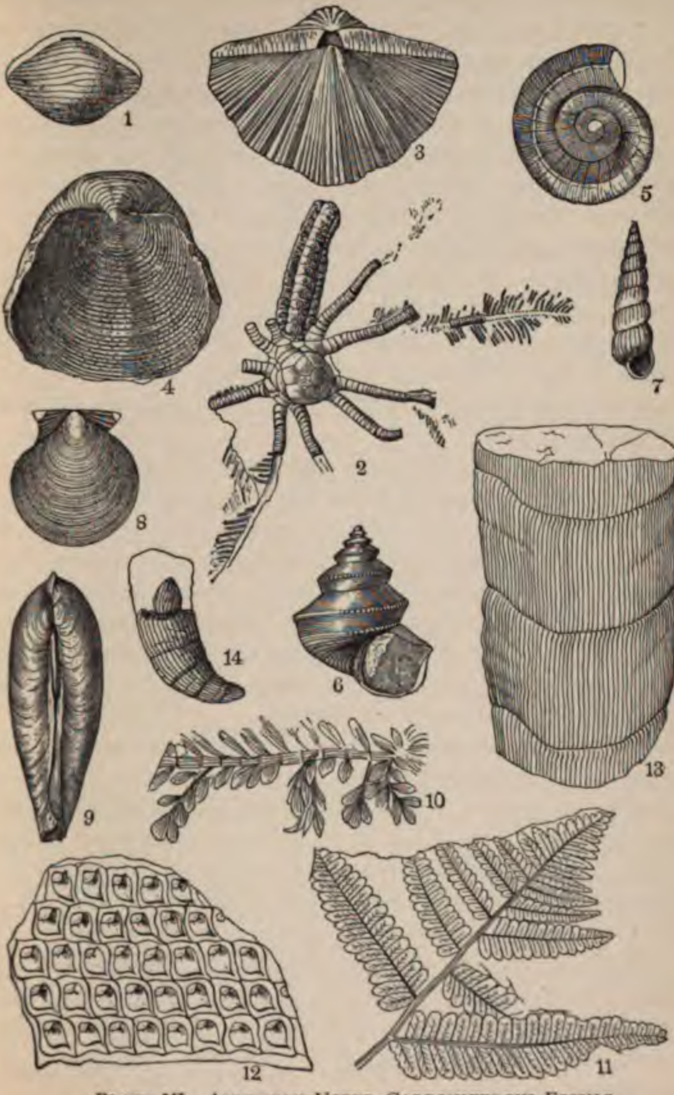

PLATE VI. AMERICAN UPPER CARBONIFEROUS FOSSILS

extinct division, *Palæocrinoidea,* none of which passed over into the Mesozoic era. Of the long list of Crinoids found in the rocks of this system may be mentioned: *Actinocrinus, Platycrinus, Rhodocrinus, Onychocrinus* (V, 6), *Æsiocrinus* (VI, 2).

The *Echinoids,* or sea-urchins, are still far less abundant than the Crinoids, but they are much more numerous and varied, and of larger size than they had been before. The Carboniferous sea-urchins are, like those of the preceding periods, members of the ancient and now extinct subclass, *Palæoechinoidea,* and the commonest genera are *Melonites* (V, 7), *Oligoporus,* and *Archæocidaris.* In addition to these should be noted the beginning of the modern subclass, *Euechinoidea,* as the still existing genus *Cidaris* is reported from the Carboniferous.

The first known *Holothuroidea,* or Sea-cucumbers, date from this period.

Arthropoda. — The Trilobites have become rare and are soon to die out altogether; most of the species belong to the peculiarly Carboniferous genera *Phillipsia* (V, 13) and *Griffithides,* but the Devonian *Proetus* still persists. The *Eurypterids* continue, even into the coal measures, but they cannot compare in size or numbers with the great Devonian forms. *Phyllopods* and *Ostracods* are abundant, and in the coal measures are found members of the highest crustacean group, the *Decapods,* of which *Anthracopalæmon* is the best known genus of the time.

Myriapods and *Scorpions* are much commoner than in the Devonian, and the first of the true *Spiders* are found here. Insects likewise show a great increase in numbers, though the Orthopters and Neuropters are still the principal orders represented. Many of the Carboniferous insects are remarkable for their great size, some of them measuring nearly a foot across the extended wings. The character of the vegetation has a very direct influence upon insect life, and the monotonous, flowerless Carboniferous forests could not have supported butterflies, bees, wasps, ants, or flies. No insects of these groups have been found in the rocks of that system, and it is not yet certain whether even beetles were then in existence.

The land life of the Carboniferous seems to be very much more varied and luxuriant than that of the Devonian and it probably was so in reality. It must be remembered, however, that the immense development of fresh-water and marshy deposits in the Carboniferous was much more favourable to the preservation of such fossils than any conditions that the Devonian had to offer. Part, at least, of the striking difference in the terrestrial fossils of the two periods is to be accounted for in this way.

The **Bryozoa** become much more important than they had been before, and contribute materially to the formation of the limestones. Characteristic Carboniferous genera are the screw-shaped *Archimedes* (V, 8), and *Chætetes*, while *Fenestella* continues to be very abundant.

The **Brachiopoda** have undergone a marked diminution, as compared with those of the Devonian, though they are still very common. Genera of long standing, like Atrypa and Pentamerus, have died out, but others, like *Chonetes* (V, 4), *Spirifera* (V, 5; VI, 3), *Orthis*, and *Rhynchonella*, are still represented by many species, but most important of all the Carboniferous genera is *Productus* (V, 3; VI, 4), which has a very large number of species, among them *P. giganteus*, the largest known brachiopod. The genus *Terebratula*, which became exceedingly abundant in the Mesozoic periods, has its beginning in the Carboniferous, though we have already found the family represented in the Devonian.

Mollusca. — The Bivalves are somewhat more abundant than in the earlier periods. Examples of these are *Aviculopecten* (VI, 8) and *Allorisma* (VI, 9). Of Gastropods, the same genera that occur in the Silurian and Devonian are continued into the Carboniferous, such as *Bellerophon* (V, 10), *Euomphalus* (VI, 5), *Pleurotomaria* (VI, 6), *Loxonema* (VI, 7), *Platyceras* (V, 9), with the interesting addition of the most ancient land-shells yet discovered. The genus *Conularia* (V, 12), referred to the Pteropods, is common. Among the Nautiloid Cephalopods, *Orthoceras* still persists, but this group reaches its acme in the number and variety of the coiled shells, many of which represent new genera, such as *Cycloceras*, *Trigonoceras*, etc. The Nautiloids have shells ornamented with prominent ridges or tubercles. The Ammonoids continue to be represented by *Goniatites* (V, 11), but the Carboniferous species of this genus display an advance over those of the Devonian in the greater complexity of their sutures, looking forward to the remarkable condition attained in Mesozoic times.

Vertebrata. — It is in this group that the most marked advances of Carboniferous life are to be observed, and the incipient stages of Mesozoic development are clearly shown. The extraordinary and bizarre Ostracoderms have become extinct, though the Arthrodirans continue into the coal measures.

The *Selachians* are numerous and varied, and some of them highly specialized. *Acanthodes* is a small shark covered with a dense armour of exceedingly minute square scales, and the fins are supported by a heavy spine along their anterior borders. Another remarkable shark is *Pleuracanthus* (a Permian species is shown in Fig. 145), which has many features in common with the Dipnoi, such as the shape of the tail, the character of the pectoral fins, and the bones which form a roof for the skull, while the skin is naked. Isolated fin-spines and teeth show that many other kinds of sharks existed in the Carboniferous, in some of which the teeth were converted into a crushing pavement, adapted for a diet of shell-fish.

The *Dipnoi* continue, though in diminished numbers, and their most prominent representative is the genus *Ctenodus*.

The *Crossopterygians* are much less abundant than in the Devonian; the commonest American genus is *Cœlacanthus*, which, though unmistakably a member of this group, has assumed the form of a bony fish, and looks much like a chub.

The *Actinopterygians* are still represented only by the Ganoid suborder; these hold their own and even increase their numbers, many new genera replacing those of Devonian times. *Eurylepis*, *Palæoniscus*, *Eurynotus*, and *Cheirodus* are the best known genera; they are all of moderate size and in appearance are not strikingly different from modern fishes.

The *Amphibians*, which we have seen reason to believe existed in the Devonian, are of greatly increased importance in the Carboniferous. At the present time the Amphibia are represented by the dwarfed and specialized frogs and toads, newts and salamanders, which give but an imperfect notion of the structure of the extinct members of the class. The Carboniferous Amphibia all belong to the extinct order *Stegocephala*, in which the skull is well covered with a roof of sculptured bones, and which are of moderate or small size, not exceeding seven or eight feet in length and mostly much smaller. The backbone is not ossified, the limbs are weak, the tail short and broad, and in many forms the belly is protected by an armour of bony scutes. An extraordinary number of genera of Carboniferous *Stegocephala* are known, most of them like the Salamanders in shape, but some are elongate, slender, and of snake-like form. Examples are *Archegosaurus*, *Branchiosaurus*, *Dendrerpeton*, *Ptyonius*, and many others.

CHAPTER XXVII

THE PERMIAN PERIOD

THE name *Permian* was given by Murchison in 1841 to a series of rocks which are very extensively developed in the province of Perm in Russia. In North America the Permian followed upon the Carboniferous with hardly a break, so that the distinction between the two systems must be made entirely upon the fossils, which change very gradually, by drawing a somewhat arbitrary line of demarcation. In consequence, many geologists, especially in this country, regard the Permian as a mere subdivision of the Carboniferous. Its relations with the overlying Triassic system are, however, nearly as close, and by some authorities it has been referred to the latter. The Permian is, on the whole, distinctively Palæozoic, but it has several features which mark it out as transitional to the Mesozoic.

		TEXAS	PENNSYLVANIA
Permian System.	Upper Series.	Double Mountain Beds.	
	Middle Series.	Clear Fork Beds.	
	Lower Series.	Wichita Beds.	Upper Barren Measures.

DISTRIBUTION OF PERMIAN ROCKS

American. — Toward the end of the Carboniferous there was in the low-lying Appalachian coal field a slowly progressive movement of elevation, resulting in the draining and drying up of most of the region over which the peat bogs had been extended. The movement spread east, north, and south, leaving in the middle of the region a smaller area in which the conditions of the coal measures continued very much as before. In the northern part of the Acadian province Permian beds overlie the coal measures in Prince Edward Island, Nova Scotia, and New Brunswick. These beds are soft red shales and sandstones, which were laid down in closed basins, not in the sea. In Pennsylvania and West Virginia the Permian beds follow directly and without any break upon the Upper Productive stage of the coal measures: they are called the Upper Barren Measures, and consist of 1000 feet of sandstones and shales with some limestone and a few seams of coal. The character of these beds is entirely like that of the coal measures, to which they were once referred, and their reference to the Permian is due to the marked change which has come over the vegetation. South of West Virginia no Permian beds have been found in the Appalachian area, owing to the elevation of this part of the region at the close of the Carboniferous, but the Permian occurs in Illinois.

As we proceed westward and southward through Missouri into Nebraska, Kansas, and Texas, we find the Permian assuming much greater importance, and becoming more and more prominently developed in extent and thickness. A study of this region reveals the fact that only a part — the lower — of the Permian is developed in the Acadian and Appalachian areas. At the end of the Lower Permian the entire series of the coal measures east of the Mississippi River was elevated and the deposition of strata checked. In the region beyond the Mississippi the Permian beds thicken southward, attaining in southern Kansas a thickness of 2000 feet, and in Texas of more than 5000 feet. The Ouachita Mountains separate the Texas and Kansas areas, which were probably covered by distinct bodies of water.

The lowest beds of the system, in this western region, are shales and limestones, which carry a transitional fauna of mingled Carboniferous and Permian types, followed by a characteristically Permian assemblage. In southwestern Kansas the sea was then excluded and salt lakes and lagoons took its place, in which sandstones and shales, with some dolomite, were accumulated, while masses of gypsum and rock salt were precipitated from the dense brines. These chemical deposits are now of much commercial importance.

In Texas the Lower Permian (*Wichita* beds) is principally composed of sandstones and clays, in which some marine and some land fossils occur. The Middle Permian (*Clear Fork* beds) is largely made up of limestones, and represents a transgression of the sea westward, for these strata often rest directly upon the coal measures, without the intervention of the Wichita. In the Upper Permian (*Double Mountain* beds) we find evidences of a closed basin, like that of Kansas and Oklahoma, in the numerous beds of gypsum, and in the quantity of salt which impregnates the shales and clays. Occasional incursions of the sea into this basin are indicated by the interbedded bands of fossiliferous limestone. Westward from Texas the inland Permian sea extended to the Pacific land area, and in it were laid down the rocks of this age found in southern Utah; these are masses of sandy shales, with much disseminated gypsum and very few fossils. In the Grand Cañon district the Permian beds are remarkable for their rich colouring. The inland sea also extended northward around the Colorado islands, and traces of its presence are found to the west in the 650 feet of Permian sandstones and shales in the Wasatch Mountains. Whether the Permian strata have all been swept away from Utah west of the Wasatch and from Nevada, or whether they were never deposited there, is a question that cannot yet be answered. In all this great interior sea of the West there is evidence that the deeper waters of Carboniferous times gradually gave place to shallow-water conditions in the Permian.

Foreign. — In Europe the Permian is developed in two entirely distinct facies or aspects. In central and western Europe the disturbances which closed the Carboniferous resulted, in many places, in a marked unconformity between the Carboniferous and the Permian, while in other regions there is a gradual transition from one system to the other, as in North America. The result of these oscillations was the formation of a great inland sea, extending from Ireland to central Germany, in which were laid down thick masses of red sandstones, shales, and marls. Occasionally the ocean broke into this closed basin, bringing a marine fauna with it, but only for comparatively short times. The disturbances continued during the Permian period itself, in consequence of which the Upper Permian has an entirely different distribution from the Lower, overlapping the latter in various directions, and resting upon Carboniferous and older strata. Volcanic eruptions were frequent and extensive, and great masses of eruptive rocks are interbedded in the Permian of England, Germany, and southern France. In north Germany were formed enormous deposits of rock salt, some of them many thousands of feet in thickness.

Southern Europe and Russia have an entirely different aspect or facies of the Permian. In the former region the development is marine, with an abundant marine fauna, which displays a gradual transition from that of the Upper Carboniferous. In the Alps are sandstones and limestones, and in Sicily most interesting transitional limestones. The Mediterranean belt was thus part of the great ocean, while northwestern Europe was covered by closed seas and salt lakes.

In Russia the Permian covers thousands of square miles; its lowest member shows the presence of a sea which extended from the Arctic Ocean, along the west flank of the Ural Mountains, to the extended Mediterranean. Later, however, a closed basin was formed in Russia also, in which sandstones, marls, limestones, and gypsum were deposited. Occasional irruptions of the ocean are indicated by strata bearing marine shells.

The marine facies of the Permian recurs in Asia, in the valley of the Araxes, in Bokhara, and in the Salt Range of northern India. The Arctic islands of Spitzbergen and New Scotland display Permian beds.

The Permian of the Southern Hemisphere is of remarkable interest, and will be briefly considered in a section at the close of the chapter.

PERMIAN LIFE

We have to note, in the first place, that the life of the Permian is transitional between that of the Palæozoic and of the Mesozoic eras, transitional both in the animals and plants. Here we find the last of many types which had persisted ever since Cambrian times, associated with forms which represent the incipient stages of characteristic Mesozoic types, together with others peculiar to the Permian.

Plants. — The flora of the Lower Permian is decidedly Palæozoic in character, and that of the Upper Permian as decidedly Mesozoic, so that if the line dividing these two great eras were drawn in accordance with the vegetation, it would pass through the Permian. Even in the Lower Permian, however, the change from the Carboniferous flora is a marked one. The great tree-like Lycopods, *Lepidodendron* and *Sigillaria*, which were so abundant in the Carboniferous forests, have become very rare; none of the former genus and only two of the latter have been found in the Upper Barren Measures of Pennsylvania and West Virginia. The *Calamites* continue in hardly diminished numbers and importance. The *Ferns* are exceedingly abundant and varied, and tree-ferns seem to be more common than they had been before. Especially characteristic genera of these plants are *Pecopteris*, *Callipteris* (Pl. VII, Fig. 5), *Cynoglossa*, *Neuropteris*, *Sphenopteris* (Pl. VII, Fig. 6), etc. The *Gymnosperms* mark a notable advance; in addition to the ancient *Cordaites*, are true Cycads (*Baiera*) and Conifers; of the latter are found yew-like forms, *Walchia*, *Saportia*, with leaves nearly four inches wide, and *Gingko*.

In the Upper Permian Lepidodendron, Sigillaria, and Calamites are quite unknown, though probably a few stragglers still existed, and the flora is made up of *Ferns*, *Cycads*, and *Conifers*, the Angiosperms still being entirely absent.

Cœlenterata. — The Corals are still mostly of Palæozoic type and belong to Carboniferous genera, but some of the modern Hexacoralla have appeared.

Echinodermata. — This group has dwindled in the most remarkable way, and instead of the great forests of Crinoids which flourished in the Carboniferous seas, are found only occasional specimens.

Arthropoda. — The last few stragglers of the genus *Phillipsia* indicate the extinction of the great Palæozoic group of Crustacea, the Trilobites, which henceforth we shall meet with no more, and the Eurypterids have entirely disappeared. Little is known concerning the other Arthropods of this period.

Bryozoa are prominent in all marine formations, sometimes forming reefs.

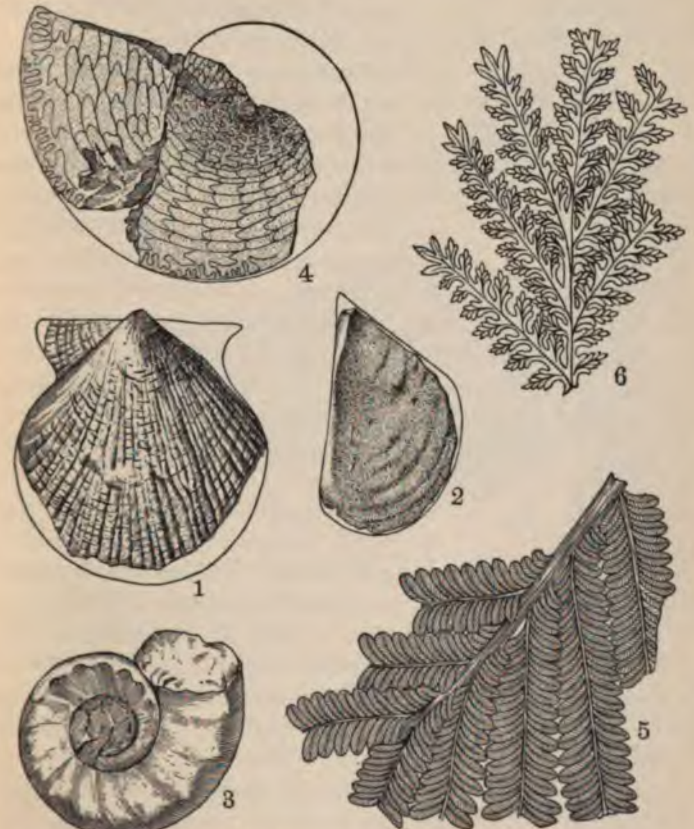

PLATE VII. AMERICAN PERMIAN FOSSILS

1. Aviculopecten occidentalis. 2. Myalina permiana, 2/3. 3. Nautilus Winslowi. 4. Medlicottia Copei, 2/3. 5. Callipteris conferta, 1/2. 6. Sphenopteris coriacea, 3/4. (Figs. 1-4 after C. A. White. Figs. 5, 6 after Fontaine and I. C. White.)

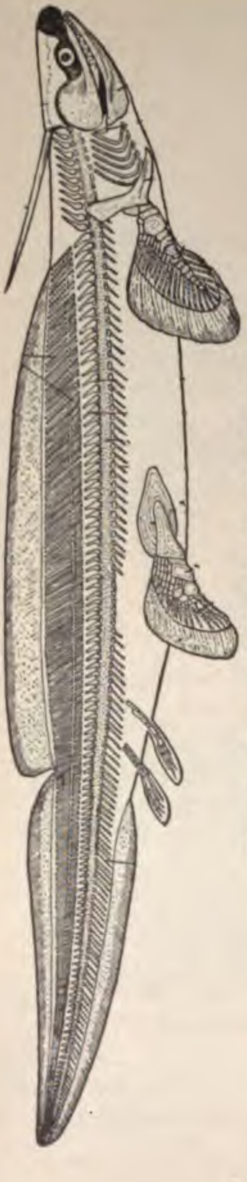

FIG. 145.— Pleuracanthus Decheni, 1/3. (Dean after Fritsch.)

The **Brachiopoda** are still very abundant, especially in the Lower Permian; they are closely allied to those of the Carboniferous, and, as in that period, the *Productids* play the most important rôle, though many of the species are peculiar to the Permian.

Mollusca. — In this group very striking changes are to be noted. The Bivalves increase materially in variety, and in addition to ancient genera like *Aviculopecten* (VII, 1) and *Myalina* (VII, 2) the Permian of India has many new forms, such as *Arca, Lucina, Lima*, etc. The Gastropods require no particular mention, except for the great abundance of the genus *Bellerophon* (Pl. V, Fig. 10). It is among the Cephalopods that the great advance takes place. *Orthoceras* and *Gyroceras* continue from the older periods, and many species of the genus *Nautilus* (VII, 3) are added, but the chief fact consists in the presence of Ammonoids with highly complex sutures, far exceeding, in this respect, the Goniatites of the Carboniferous, some of which continue to exist alongside of the more advanced forms. The more important new genera of Ammonoids are *Medlicottia* (VII, 4), *Ptychites*, *Popanoceras*, *Waagenoceras*, which have been found in Texas, Sicily, Russia, and India. The presence of these remarkable shells gives a strong Mesozoic cast to the Permian fauna.

Vertebrata. — The *Fishes* are still of Carboniferous types, and many of the same genera occur, while new ones are brought in. To the Sharks are added the curious *Menaspis,* which is armed with numerous long and curved spines. Among the Dipnoi the genus *Ceratodus,* very closely allied to the modern lung fish of Australia, makes its first appearance.

The *Amphibia* are represented, as in the Carboniferous, by the Stegocephala, and several of the older genera persist, but many new forms appear for the first time, several of which much surpass the Carboniferous genera in size.

The most important character that distinguishes the life of the Permian from that of all preceding periods is the appearance in large numbers of true *Reptiles.* There is no reason to suppose that such a variegated reptilian fauna can have come into existence suddenly, and their ancestors will doubtless be discovered in the Carboniferous; but while no true reptiles are certainly known from the latter, in the Permian they are the most conspicuous elements of vertebrate life. These reptiles represent two orders, one of which, the *Proganosauria,* is a very central group, from which many other reptilian orders appear to be descended; *Proterosaurus* and *Palæohatteria* are the most important Permian genera of this group. The second order, that of the *Theromorpha,* is remarkable for its many approximations to the structure of the mammals, as well as for the curious and bizarre forms which many of its members assume. This is the only order of reptiles which has so far been found in the Permian of Texas, but of this group no less than 15

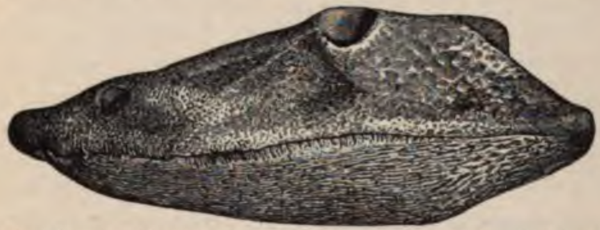

FIG. 146. — Permian Stegocephalan, *Eryops megacephalus,* 1/7. Skull seen from the side. (Cope.)

genera and 34 species have been found in these beds. The order continues up into the Trias, where it becomes exceedingly diversified and more anomalous than ever, but is not known from any later period.

Examples of the Texas Theromorphs are *Pantylus*, *Bolosaurus*, *Diadectes*, *Empedocles*, etc.

The Permian of the Southern Hemisphere

The Permian has in the Southern Hemisphere a very remarkable and very uniform development, and brings up some problems of the greatest interest. In peninsular India, South Africa, Australia, and South America the same phenomena are repeated, phenomena which have not been satisfactorily explained.

The formation is particularly well developed in Australia, occurring from Tasmania to Queensland, but is best known in Victoria and New South Wales, where these beds cover many hundreds of square miles. The strata called "Permo-Carboniferous" are more than 2000 feet thick, and in them occur numerous beds of boulders of all sizes, some of them weighing many tons. Many of these boulders have been transported long distances from their parent outcrops, and are of angular shape and often plainly scratched and scored. The boulders are held together by aqueous deposits, sand, or mud, and fossiliferous marine strata are associated with them. In one locality are two such marine formations, each with several boulder beds, and between them are intercalated 230 feet of coal measures, carrying from twenty to forty feet of coal seams. The pavement of older rocks, upon which the boulder-bearing series is laid down, is of different ages in different places, but very frequently this pavement is grooved and polished, with the formation of *rôches moutonnées*, as if by the passage of a glacier.

India has a similar series of deposits, which, however, are not marine, but were laid down in an inland sea, apparently of fresh water. South of the Himalayas is found, resting upon a foundation of metamorphic rocks, a great mass of sandstones and shales, called the *Gondwána* series, which probably represents the marine succession from the Permian to the Jurassic inclusive. In the lower members are found great boulder beds, with boulders up to fifteen feet in diameter, which have been carried for several miles. In some of these beds the boulders are scored with parallel grooves and beautifully polished. As in Australia, the pavement of older rocks is cut into *rôches moutonnées* and marked with long parallel scorings. The coal-bearing rocks of India overlie the boulder beds, and are regarded as Permian.

In South Africa the Karoo series, partly Permian and partly Triassic, rises abruptly near the coast, though retaining the horizontal position, in the mountain ranges called Quatlambabergen, Drakenbergen, and Stormbergen. Here likewise have been found beds of scratched and polished boulders and pavements of grooved and polished rocks, just as in Australia and India.

In South America, rocks having the character and fossils of the lower Gondwána beds have been found in the Argentine Republic and in southern Brazil, the latter with boulder beds.

Permian life in the Southern Hemisphere is as characteristic as the strata themselves. The flora is entirely different from that of the Carboniferous, which is also found in Australia, southern Africa, and South America. This Permian flora contains no Lepidodendron, Sigillaria, or Calamites, and has a decidedly Mesozoic aspect, being made up of Ferns, Horsetails, Cycads, and Conifers. The most characteristic plant is the fern *Glossopteris*, whence this vegetation is frequently called the "Glossopteris Flora," and another very abundant and widely spread fern is *Gangamopteris*. *Phyllotheca* and *Vertebraria* are the commonest Horsetails, and of the Conifers, *Voltzia* (see Fig. 148,

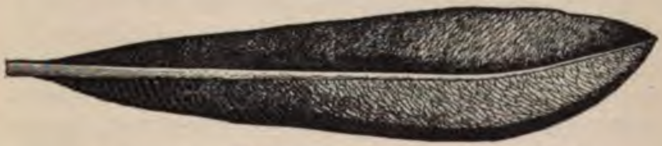

FIG. 147.—Glossopteris indica. (Medlicott and Blanford.)

p. 449) is the most characteristic. In northern lands the plants of this flora do not become important, and some do not even make their first appearance, till Triassic or even Jurassic times. The Glossopteris Flora has an enormously wide distribution; it is found in Tonquin, India, Afghanistan, southern Africa, Australia, and South America, and has recently been discovered in Italy.

The marine fauna of the Southern Hemisphere is not notably different from that of the Northern. The land fauna of Amphibia and Theromorphous Reptiles is very nearly the same in India, Africa, and South America; and there is a marked affinity with the Permian Vertebrates of Russia and Texas. These animals have not yet been discovered in Australia.

The facts regarding the Permian of the Southern Hemisphere are very puzzling, and have been much debated. The boulder beds and the striated, polished pavements upon which they rest are just such evidence as has been relied upon to prove the reality of the Glacial Age, one of the latest episodes in the history of the earth. Hence many geologists have concluded that there was a glacial age in the Permian of the southern continents. To such an inference, however, there is one serious objection: namely, the flora and fauna which then flourished on those lands and in the adjoining seas. In the undoubted Glacial Age of the Pleistocene, not only do the scorings and polishings, the moraines and erratic blocks, require the presence of vast glaciers for their explanation, but the fossils are also in harmony with this conclusion, and themselves offer excellent evidence of a cold climate. In the southern Permian, on the contrary, we find interstratified with the boulders beds containing every evidence of a luxuriant land and marine flora and fauna, such as could not possibly have existed on or around a continent buried under great ice-sheets, as is Greenland to-day. That the boulder beds and their polished pavements are the work of ice, there can be little doubt, but it seems much more likely that the glaciers were ice-streams, descending from highlands, than that Permian Australia, for instance, was buried under eleven successive ice-sheets. Probably, also, the winters were sufficiently cold to allow the formation of floating ice.

From the distribution of the animals and plants of the southern Permian, it is altogether probable that there was land communication between India, southern Africa, and South America, and less directly with Australia.

CLOSE OF THE PERMIAN

One of the greatest revolutions in the history of the North American continent culminated at the end of the Permian, though it probably began in the Carboniferous. With the exception of the mountain making at the close of the Ordovician, the Palæozoic era in North America had been a time of slow, even development, with many oscillations of level, but without violent disturbances, and with singularly few manifestations of volcanic activity. A little more land was added to the northern area during each period, but, so far as we can trace it, the geography of the Ordovician does not seem to have been very different from that of the Carboniferous. Throughout this long era, doubtless more than equal to all subsequent time, the Appalachian geosyncline had been sinking, though with many shifts and oscillations, under an ever-increasing load of sediment, until the great trough contained a thickness of 30,000 to 40,000 feet of strata. Eventually the trough began to yield to the lateral compression exerted by the shrinking crust, and its contained strata were thrown into folds, or fractured by great overthrust faults. Thus, in place of a sinking sea-bottom along the shore of the great Interior Sea, rose the Appalachian Mountains, which in their youth may have been a very lofty range, rivalling the Alps in height. This range extends from the Hudson River to Alabama; another range from Newfoundland to Rhode Island, and a third, the Ouachita Mountains of Arkansas, are attributed to the same set of disturbances, which thus made themselves felt for a distance of 2000 miles. In the West the results of this revolution are much less clearly shown. Either at the close of the Carboniferous or of the Permian, the Great Basin region, of western Utah and eastern Nevada, was upheaved into land, and at the present time the surface rocks over most of this region are

Carboniferous. It is, however, not at all impossible that the thin Permian may have been stripped away by denudation, as it has been over nearly all of the northern plateau of Arizona.

At the time when the eastern part of the Great Basin was thus converted into land, the ancient land area of its western border was depressed beneath the sea. It is probable that these two movements were connected, though they may have been separated by a considerable interval of time. In Nevada west of 117° 30′ W. longitude no Palæozoic rocks have been found, and the Trias rests directly upon the Archæan.

However they may be explained, the geographical revolution which closed the Palæozoic era was accompanied by the most profound and far-reaching changes which have ever occurred in the recorded history of life, after which we find ourselves in a new world. It is probable that the change was a relatively rapid one, but there are sufficient connections between the faunas and floras of the two eras to show that the later were derived from the earlier, and that the gaps are due to the imperfections of the record.

CHAPTER XXVIII

MESOZOIC PERIODS — TRIASSIC

The Mesozoic era, so far as we can judge, seems to have been much shorter than the Palæozoic; in North America Mesozoic rocks are very much more important and widely spread in the western half of the continent than in the eastern. The latter region was, in a measure, completed by the Appalachian revolution, and subsequent growth consisted merely in the successive addition of narrow strips to the coast-line, but in the West many great changes were required to bring the land to its present condition.

The life of the Mesozoic constitutes a very distinctly marked assemblage of types, differing both from their predecessors of the Palæozoic and their successors of the Cenozoic. In the course of the era the Plants and marine Invertebrates attained substantially their modern condition, though the Vertebrates remain throughout the era very different from later ones. Even in the Vertebrates, however, the beginnings of the newer order of things may be traced. In the earlier two periods, the Triassic and Jurassic, vegetation is almost confined to the groups of *Ferns*, *Cycads*, and *Conifers*, but with the Cretaceous come in the *Angiosperms*, both *Monocotyledons* and *Dicotyledons*, and since then the changes have been merely in matters of detail.

With few exceptions, the ancient *Tetracoralla* have all disappeared, and the modern *Hexacoralla* take their place. The *Echinoderms* are all markedly different from the Palæozoic types. The *Cystids* and *Blastoids* have died out, and the *Crinoids* have been revolutionized, the *Palæocrinoidea* being replaced by the *Neocrinoidea*. Likewise the modern sea-urchins, *Euechinoidea*, replace the ancient *Palæoechinoidea*, and many Mesozoic genera of the former group are still living in our modern seas. The *Starfishes* also assume their modern condition. *Brachiopods* are far less abundant and diversified than they had been in the Palæozoic, and belong, for the most part, to different families, while the *Bivalve* and *Gastropod Mollusca* increase to a wonderful extent. Especially characteristic are the marvellous wealth and variety of the *Ammonoid Cephalopods*, which disappear at the close of the era. The *Dibranchiate Cephalopods*, with internal shells, make their first appearance in the Mesozoic, and one group of them, the *Belemnites*, is almost exclusively confined to the era. The *Arthropods* show the same revolutionary changes. Among the *Crustacea*, the *Trilobites* and *Eurypterids* have gone out, but all the modern groups are well represented, though many of the Mesozoic genera are no longer to be found in the seas of to-day. *Insects* reach nearly their modern condition, so far as the large groups are concerned, butterflies, bees, wasps, ants, flies, beetles, etc., being added to the older orthopters and neuropters.

Fishes become modernized before the close of the era, the *Bony Fishes* having acquired their present predominance. The *Amphibia* take a subordinate place, and after flourishing for a time, the great *Stegocephala* die out, leaving only the pygmy salamanders and frogs of the present. *Birds* and *Mammals* make their first appearance, the former advancing rapidly to nearly their present grade of organization, though not reaching their present diversity, while the mammals remain throughout the era very small, primitive, and inconspicuous. The most significant and characteristic feature of Mesozoic life is the dominance of the *Reptiles*, which, in size, in numbers, and in diversified adaptation to various conditions of life, attain an extraordinary height of development. The Mesozoic is called the "Era of Reptiles," because these were the dominant forms of life. They filled all the rôles now taken by birds and mammals; they covered the land with gigantic herbivorous and carnivorous forms, they swarmed in the sea, and, as literal flying dragons, they dominated the air. At the present time there are only four orders of reptiles in existence, and of these only the crocodiles and a few snakes attain really large size.

In the Mesozoic era no less than twelve reptilian orders flourished, and nearly all of them had gigantic members. Some were the largest land animals that ever existed, and the sea-dragons rivalled the whales in size. Nothing so clearly shows that the Mesozoic era is a great historical fact, as the dominance of its reptiles.

The Mesozoic climates offer some difficult problems. In general, the climate was mild, as is shown by the plants found in the Mesozoic rocks of Arctic lands, for in Greenland, Alaska, and Spitzbergen was a luxuriant vegetation of warm temperate type. On the other hand, certain geologists have maintained the existence of distinct climatic belts in the Mesozoic, indicating equatorial, northern, and southern zones, but by others this interpretation is denied.

The Mesozoic era comprises three periods, — the Triassic, Jurassic, and Cretaceous.

THE TRIASSIC PERIOD

The Triassic period is so named from the very conspicuous threefold subdivisions of this system of strata in Germany, where its rocks were first studied in detail, and where they occupy a greater area than in any other European country. The German Trias is, however, not the usual and normal facies of the system, but a very peculiar one, and cannot be taken as the standard of comparison for most other countries.

The Trias of North America is displayed under three very different facies, — that of the Pacific coast, which is marine; that of the interior, which is lacustrine; and that of the Atlantic border, which is estuarine. Owing to the absence of fossils common to all it is not yet possible accurately to correlate the three facies, but the divisions of the Pacific and Atlantic borders are given in the following table: —

	Pacific Border	Atlantic Border
Triassic System.	Bajuvaric Series.	? Newark Series.
	Tirolic Series.	
	Dinaric Series.	
	Scythic Series.	

DISTRIBUTION OF THE TRIAS

American.— In the early part of the Triassic period both North and South America extended farther eastward than they do now. It is a remarkable fact that no marine deposits of this period are known to exist on the Atlantic slope of either continent, but numerous isolated bodies of brackish and fresh-water deposits occur in lines approximately parallel to the present eastern coasts of North and Central America. At some time during the period, perhaps in its latter half, there were formed in the northern continent a series of long, narrow troughs, running closely parallel to the trend of the Appalachian Mountains, though separated from that range by the ridges of crystalline, metamorphic rocks which had formed the western border of the Appalachian land in Palæozoic times. In these troughs water was accumulated, forming sometimes tidal estuaries, sometimes fresh-water lakes, streams, and bogs. A great mass of rocks was laid down upon the slowly subsiding bottoms of the troughs. The thickness of these rocks has not yet been definitely measured, but is very great, — so great that some authorities maintain that their formation must have begun in the Permian, at least in Pennsylvania.

At the present time the Triassic rocks of the Atlantic border are found in separate patches from Nova Scotia to South Carolina, the largest continuous area extending from the Hudson River across New Jersey, southeastern Pennsylvania and Maryland, into Virginia. Other areas occur in Nova Scotia, Prince Edward Island, Massachusetts, Connecticut, and several scattered ones in Virginia and North Carolina. The rocks are prevailingly red sandstones, but coarse conglomerates and breccias are common at the base of the series; ferruginous shales are frequently interbedded with the sandstones, and some thin beds of impure limestones are locally developed. In Virginia and North Carolina the conditions of Carboniferous times were once more established, and in the peat bogs and swamps of those regions workable coal of good quality was accumulated. This coal can be distinguished from that of the preceding periods by the character of the plants of which it is composed. The rocks of this *Newark* series were evidently formed from the waste of the granite and crystalline schists in the neighbouring hills, for the sandstones are largely felspathic and micaceous. The sedimentary rocks of the Appalachian range did not contribute to the formation of the Triassic deposits, their drainage being to the west, for the metamorphic ridges to the eastward effectually cut off the Appalachian streams from the Triassic estuaries.

It is still a question whether these inland bodies of water were originally separated or continuous, though it seems probable that all the areas lying to the southwest of the Hudson were thus connected, while those of the Connecticut valley and Nova Scotia may have been formed in another continuous body of water. Evidences of tidal action are to be seen in the rocks of both of these estuaries. Fossils are rare in these rocks, and none of marine origin have been found; land plants and the footprints of land animals are the commonest fossils, but in some localities fishes are quite numerous.

The sedimentary rocks of this estuarine Trias are much faulted, and some of the dislocation appears to have taken place while the sediments were still in process of deposition. The beds are also cut by many dikes of diabase, and sheets of the same are intercalated between the strata. Some of these sheets are contemporaneous lava flows, and indicate much volcanic activity during Triassic times; others are intrusive, and, with the dikes, belong to a later series of disturbances. These igneous rocks everywhere accompany the Triassic strata, from Nova Scotia to North Carolina.

The rarity of fossils makes the exact reference of the Newark series a matter of uncertainty, but the evidence favours the conclusion that these rocks belong in the upper part of the Triassic system.

In the interior region a large part of the continent was covered by a great, but shallow inland sea, which must have been shut off from the ocean. What are now the mountain ranges of Colorado formed one long island, reaching from Wyoming to New Mexico, On each side of that island were the waters of the shallow inland sea that extended westward across the site of the Wasatch Mountains to the eastern shore of the Great Basin land, which was upheaved at the close of the Carboniferous or Permian; eastward the sea extended to an unknown distance. Western Texas, northwestern New Mexico, and the adjoining part of Arizona were covered by these waters, while nearly all of Mexico was land, except an apparently isolated body of water in Sonora. The Mexican land, joined to the Great Basin land, enclosed the sea on the south and west; northward its waters ended a little beyond the forty-ninth parallel of latitude, and did not extend so far west as the Selkirk and Gold ranges of British Columbia. In some places this inland sea was established by transgression over ancient lands; in Wyoming, for example, Triassic beds rest upon pre-Cambrian crystalline rocks.

Over this great area were deposited a series of rocks, chiefly sandstones, containing much gypsum and some salt, an evidence of salt-lake conditions; but in southwestern Colorado, northwestern New Mexico, and western Texas fresh-water conditions prevailed, at least toward the end of the period. The thickness of the strata varies from 600 to 2000 feet. In this inland Trias very few fossils of any sort have been found, and none of them are marine. In many places the reference of these beds must be made upon purely stratigraphical grounds.

On the western shore of the Great Basin land we find an entirely different state of things from that which obtained on the Atlantic border or in the interior region. The part of the Great Basin area which had been land during the Palæozoic went down, allowing the ocean to extend across the site of the Sierra and to cover western Nevada, and in British Columbia it submerged the land eastward across the mountains. The Pacific coast-line was thus considerably to the east of its present position, and from it a gulf extended into southeastern Idaho. Marine Trias also recurs on the shores of Alaska. The Pacific coast Trias has a maximum thickness of 4800 feet, and contains representatives of nearly all the series which make up the system. Its successive faunas indicate extensive changes in the physical geography of the lands around the Pacific. In the lower Trias (*Scythic* series) the connection of our Pacific shore was with the Indian and Arctic regions; in the middle or *Dinaric* series the connection with the Arctic region is still close, but migration from the Mediterranean region had begun, while in the *Tirolic* series the relation is most intimate with the Indian and Mediterranean regions of the Old World. Hardly any of the uppermost, or *Bajuvaric*, series is found on the west coast of North America.

Foreign. — In Central America (Honduras) has been found another area of estuarine Trias like that of our Atlantic States. All South America east of the Andes was above the sea, for marine Trias is known only on the west side of the Cordilleras.

In Europe the Trias is displayed in two very different facies, that of central Europe, the production of inland seas and salt lakes, and that of southern Europe, or the Alpine facies, which is marine. In the former region the conditions of the Permian were largely continued, though the situation of the basins was often different from what it had been in the Permian. In Germany Triassic rocks cover a very wide area, extending across the southern and central parts of the empire from Poland into France. These rocks are very obviously divided into three series,—a lower division of sandstones and clays, the *Bunter Sandstone;* a middle calcareous division, the *Muschelkalk;* and an upper sandy division, the *Keuper.* The upper and lower divisions are those of the closed basins, with some formation of coal in the Keuper, while the Muschelkalk represents an invasion of the sea from the south, and contains a considerable marine fauna. Triassic deposits extend from the north of Ireland across England, and in southern Sweden is coal-bearing Keuper. In these northern lands the Muschelkalk is absent, and evidently the transgression of the sea did not extend to them. The sandy and clay deposits of England, France, and Germany were laid down in very shallow waters, while deposits of gypsum and salt indicate the presence of salt lakes. Judging from modern conditions, we may infer that in Permian and Triassic times the climate of northwestern Europe was warm and dry, evaporation exceeding rainfall.

In southern Europe the Trias was formed under very different conditions. A great sea covered all that region, extending from Spain over the site of the Alps eastward to the Himalayas, and in this region the deposits are mostly limestones, with very rich marine faunas. In the lower Trias the Mediterranean was not connected with the Pacific or Arctic oceans, but in the middle division, as we have seen, the connection was made, and Mediterranean species extended their range to California. Around the borders of the Pacific-Arctic seas were laid down the Triassic deposits of northern and eastern Siberia, Spitzbergen, Japan, New Zealand, and the west coasts of North and South America.

The peninsular part of India was still, to a great extent, covered by the inland sea which had been formed there in the Permian period (see p. 437), and part of the great Gondwána series is referable to the Trias. In South Africa part of the Karoo series is Permian, but most of it is Triassic; it consists of 8000 to 10,000 feet of shales and sandstones laid down in an inland sea. That the land connection with India persisted is indicated by the continued similarity of the land animals and plants.

THE LIFE OF THE TRIASSIC

Triassic life is entirely different from anything that had preceded it, though the way for the change was already preparing in the Permian. As we have seen, the Upper Permian, if classified by its plants alone, would be referred to the Mesozoic rather than to the Palæozoic, and we are therefore prepared to learn that the Triassic flora is very similar to that of the Upper Permian.

Plants. — Triassic vegetation is composed of *Ferns*, *Horsetails*, *Cycads*, and *Conifers*, and of such plants were the Newark coals of Virginia and North Carolina and the Keuper coals of Germany and Sweden accumulated. The Ferns are relatively somewhat less abundant than they had been in the Carboniferous, and many of them belong to the existing tropical family of the *Marattiaceæ*.

Tæniopteris, *Caulopteris*, *Clathropteris* (Pl. VIII, Fig. 5) are among the most important genera. In Virginia a magnificent fern with very broad leaves, *Macrotæniopteris*, is the most abundant and characteristic of the Triassic plants there found.

The *Lycopods* have undergone a great reduction since the Carboniferous, though a few straggling specimens of *Sigillaria* have been found in the lower Trias. On the other hand, true Horsetails of the modern genus *Equisetum* now make their first appearance, and much surpass their modern representatives in size, having stems of 4 inches in thickness. Rhizomes and stems of these plants are very common, and dense growths of them, like cane-brakes, surrounded the inland seas and salt lakes of the period.

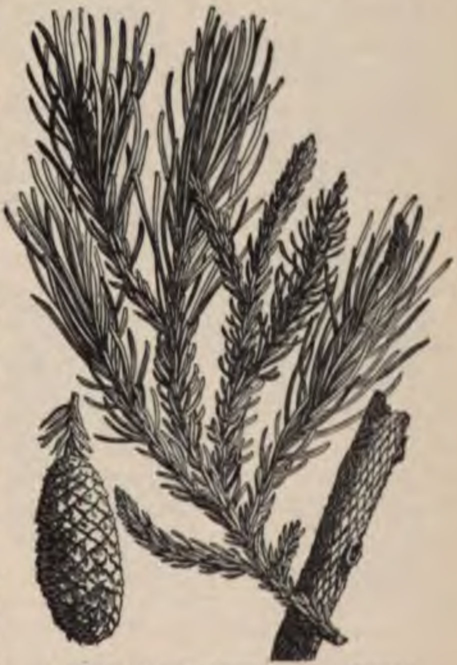

FIG. 148.— Voltzia heterophylla. (Fraas.)

Cycads with their stiff leaves abounded, growing, doubtless, on the dryer lowlands above the swamps, most of them belonging to such genera as *Pterophyllum*, *Zamites*, and *Otozamites* (VIII, 6). This group of plants is a characteristic Mesozoic one, and the era is sometimes called the "Age of Cycads." On the hills and uplands grew dense forests of Conifers, in appearance like the *Araucarians*, which are found to-day in South America, Polynesia, and Australia. *Baiera*, *Araucarites*, and the cypress-like *Voltzia* (Fig. 148), the latter much resembling the Permian *Walchia*, are common genera.

While the Triassic flora is thus different from that of the Palæozoic, it must have given to the landscapes of the period much the same appearance of graceful and luxuriant, but somewhat gloomy and monotonous, vegetation. Probably the fern forests of New Zealand give the best modern picture of these early Mesozoic woodlands.

Of marine plants, the *Calcareous Algæ* should be mentioned.

Among the animals the change from Palæozoic times is much more complete than among the plants.

Cœlenterata. — Corals abounded in the seas, wherever conditions were favourable to their growth, but the Palæozoic *Tetracoralla* have died out, and their place is taken by the modern *Hexacoralla*, though the two groups of corals approach each other so closely that the distinction is not a sharp one.

Echinodermata. — In this type a more marked change has taken place. The *Cystids* and *Blastoids* have disappeared, and the *Crinoids* have undergone a change of structure, the *Palæocrinoidea* giving way to the *Neocrinoidea*, though the latter occur only in small numbers and in character rather transitional from the older forms than typical of the new. Of the Triassic Crinoids much the commonest, and indeed the only well-known genus, is *Encrinus*, which is so characteristic of the German Muschelkalk; it resembles more the Palæozoic than the later Mesozoic Crinoids. Similarly, the ancient type of the Sea-urchins, the *Palæoechinoidea*, is all but gone, only a few persisting through the Mesozoic, while the *Euechinoidea*, which began in a small way in the Carboniferous, now come to the front. The Triassic Echinoids all belong to the subclass *Regulares*, the irregular forms not appearing till later.

Arthropoda. — The Crustacea and Insects of the Trias are not well known, and offer no features of particular interest.

The **Bryozoa** undergo a marked change in the disappearance of the ancient Fenestella-like genera.

Brachiopoda. — One of the most important changes from the Palæozoic to the Mesozoic consists in the great reduction of the Brachiopods. Even in the Trias the reduction is very marked, though several Palæozoic genera have their latest representatives in the rocks of this system; as examples, may be mentioned *Productus*, *Athyris*, and *Cyrtina*. *Koninckina* is a new genus of the Spirifer family, which is confined to the Trias. The still existing genera, *Terebratula* and *Rhynchonella*, are much the most abundant brachiopods of the period, and *Thecidium*, which later becomes important, has its beginning here.

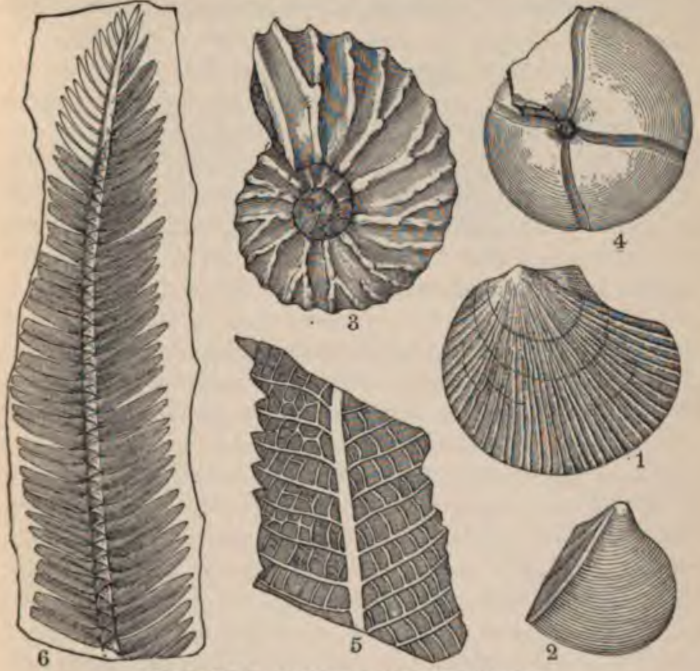

PLATE VIII. AMERICAN TRIASSIC FOSSILS

1. Monotis subcircularis. 2. Myophoria alta. 3. Trachyceras Whitneyi, 1/2. 4. Arcestes Gabbi. 5. Clathropteris platyphylla. 6. Otozamites latior. (Figs. 1–4 after Gabb. Figs. 5, 6 after Newberry.)

Mollusca. — Almost in proportion to the decline of the brachiopods is the rise of the *Pelycypoda*, or Bivalves, which now become far more varied and abundant than they had been in the Palæozoic. *Pecten*, *Monotis* (VIII, 1), *Myophoria* (VIII, 2), *Halobia*, and *Car-*

dita, may be selected as a few examples of the commoner genera. The higher forms of the class, the *Sinupalliata*, are, however, still rare. The *Gastropoda* are yet in a transition stage. Several genera, such as *Murchisonia*, *Loxonema*, etc., here make their last appearance, and mingled with them are the forerunners and earliest representatives of modern types, such as *Cerithium*, *Emarginula*, etc.

The *Cephalopoda*, and more particularly the *Ammonoids*, have already acquired a wonderful degree of abundance and variety, more than 1000 species of the latter group having already been described from the Trias. The ancient Nautiloid genus *Orthoceras*, which ranges from the uppermost Cambrian through the whole Palæozoic group, persists into the Triassic system, but not later, and numerous coiled Nautiloids with angulated and ornamented shells recall those of the Carboniferous. Of the Ammonoids some still have the comparatively simple sutures of *Goniatites*, others, like *Ceratites*, have slightly serrated sutures, while in the upper Triassic occur some shells in which the complexity of the sutures is carried farther than in any other known members of the group. Only a few of this great assemblage of genera can be mentioned; especially characteristic of the Trias are: *Tierolites*, *Trachyceras* (VIII, 3), *Meekoceras*, *Arcestes* (VIII, 4), *Ceratites*, and *Pinacoceras*. It is very interesting to observe that in the Trias occur, though but rarely, certain unusual forms of Ammonoid shells, which do not become important until the long subsequent time of the Cretaceous period. *Rhabdoceras* has a straight shell, *Cochloceras* one that is coiled in a high spiral like a gastropod, and in *Choristoceras* the coils are open. The Cretaceous genera were not derived from these Triassic anticipations, but are degenerate members of many Ammonoid families. The Dibranchiate Cephalopods, and especially the characteristic Mesozoic group of the *Belemnites*, have their earliest and most primitive representatives in the Triassic genera *Atractites* and *Aulacoceras*.

The **Vertebrata** are of extraordinary interest, and if the Trias had yielded only vertebrate fossils, it would still be apparent that great progress had been made since the time of the latest known Palæozoic beds. The *Fishes* display this progress least of all the

Vertebrates. Shark teeth are known, but not skeletons. The Dipnoan *Ceratodus* is very characteristic, continuing up from the Permian. The Crossopterygians have greatly declined, but some very large and curious fishes of this group, like *Diplurus* (Fig. 149), still linger. The Ganoids continue to be the dominant fish-type, especially of the inland waters, and are most like the existing garpikes. *Catopterus* and *Ischypterus* are representative American genera, and *Semionotus*, *Dictyopyge*, and *Lepidotus* are nearly allied European fishes.

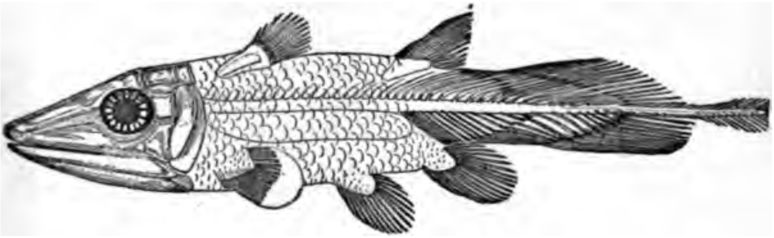

FIG. 149. — Diplurus longicaudatus. Newark shales. (Dean.)

The *Amphibia* reach their culminating importance in the Trias, the Stegocephala multiplying and diversifying in a wonderful fashion, and far surpassing the genera of the Carboniferous and Permian in size. These Amphibians have been found in North America, southern Africa, and Europe; but those of the last-named continent are much the best understood, because best preserved, the Bunter Sandstone of Germany being a treasure-house of such remains. *Mastodonsaurus*, *Cyclotosaurus*, and *Labyrinthodon* are common European genera, but there are many others. *Cheirotherium* (also European) is known only from its curious footprints, like the print of a human hand. (See Fig. 85, p. 230.)

Reptilia. — It is in this class that we find the most remarkable changes; and although reptiles are common in the Permian, the abundance and diversity of the Triassic reptiles are incomparably greater. Almost all the orders of Mesozoic reptiles are already represented in the Trias, though often by comparatively small and rare forms. The Triassic reptiles are much more common and better preserved in Europe than in America, only two orders having as yet been found here; but such American genera as do occur show that there was no essential difference between the reptilian faunas of the two continents.

The *Rhynchocephalia*, which are very near to the Permian Proganosauria, are represented by *Telerpeton* and *Hyperodapedon*. Allied to the Crocodiles are the little *Aëtosaurus* and the formidable *Belodon* (Fig. 150), the latter found also in this country. The first of the dolphin-like *Ichthyosaurs*, which become so important in the Jurassic, are sparingly found in the Trias. Another group of sea-dragons, the *Plesiosaurs*, which attain such great development in Jurassic times, is represented in the Trias by small ancestral forms, *Nothosaurus*, etc. These are of extraordinary interest, as showing the descent of the purely marine Plesiosaurs, with their swimming paddles, from terrestrial reptiles which had feet adapted for walking.

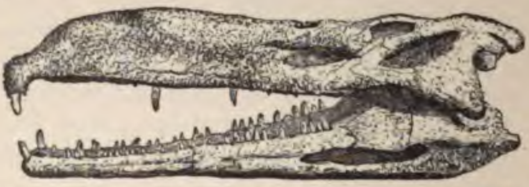

FIG. 150. — Skull of *Belodon Kapffi*, about $\frac{1}{10}$ natural size. (Zittel.)

One of the most characteristic of the Mesozoic orders of reptiles is that of the *Dinosauria*, of which the Trias has many representatives; but clearly there were very many more than have yet been found, for the Newark sandstones of the eastern United States have preserved a great variety of Dinosaurian footprints, but very few bones have been found in these rocks. The *Dinosauria* were a much diversified order of reptiles, adapted for very different habits of life: some were herbivorous, others carnivorous; some walked on all fours; others were occasionally or habitually bipedal, and walked upright after the manner of birds, with which they have many structural features in common. The gigantic size attained by some of these creatures, even in the Trias, is shown by the footprints, some of which are 14 to 18 inches in length. Of the few American forms of which the bones have been found, the best known is *Anchisaurus* from the Connecticut valley, and of the European genera, *Zanclodon*.

The earliest *Turtles* are found in the Triassic of Europe, and these first-known members of the order are as typically differentiated as any of the later members. No doubt, the Turtles originated in the Permian, in some region as yet unknown, and migrated to Europe in the Trias. The *Theromorphs*, which we found beginning in the Permian, culminated in the Trias, especially in southern Africa. Of this group there are two Triassic suborders, the *Anomodontia* and the *Theriodontia*. The former have cutting jaws, like Turtles, and may or may not possess a pair of great tusks in the upper jaw. *Dicynodon*, a genus of this suborder, has been found in southern Africa, India, and Scotland. The Theriodonts present extraordinary approximations to the mammals, and have left a great wealth of remains — some of them very large — in the Karoo beds of South Africa, and less abundantly in India.

We thus observe a notable contrast between the Triassic reptiles of Europe and North America, on the one hand, and those of south Africa and India, on the other. In the northern continents the fauna is much more diversified, and consists of Rhynchocephalia, Crocodiles, Turtles, Ichthyosaurs, Plesiosaurs, a great variety of Dinosaurs, and a few Theromorphs; and associated with these are many great Stegocephalous Amphibia. In south Africa the reptilian fauna is almost entirely composed of an extraordinary variety of Theromorphs, some of which were exceedingly curious in appearance, and in size ranged from very large to very small types. India was the meeting-ground of the northern and southern faunas, and had representatives of both.

The Trias has, as yet, yielded no Lizards, Snakes, or Pterosaurs, all of which became very important at a later date. No birds are known from this period, nor any reptiles which can be regarded as the ancestors of birds.

Mammalia. — Still another great advance in the progress of life is registered in the first appearance of the Mammals, which occurred in the Trias. Mammals are the most highly organized forms of animals; but these, their earliest known representatives, were very small and very primitive, giving little promise of being the future conquerors of the world, as they were tiny creatures which, in a measure, represent the transition from lower vertebrates upward. Two American genera, *Dromatherium* and *Microconodon*, and one European genus, *Microlestes*, have been recovered.

CHAPTER XXIX

THE JURASSIC PERIOD

THE name *Jurassic* was first used by Brogniart and Humboldt, and was taken from the Jura Mountains of Switzerland, where the rocks of this system are admirably displayed. In Europe the Jurassic has long been a favourite subject of study, because of the marvellous wealth of beautifully preserved fossils which it contains. For this reason, the Jurassic is known with a fulness of detail, such as has been acquired regarding very few of the other systems; and no less than thirty well-defined subdivisions have been traced through many countries of the Old World. For this country no such minute subdivision is as yet possible, and only the three primary divisions of the system need be cited.

Jurassic System.	Oölite	Upper Jurassic Series.	White Jura, or Malm.[1]
		Middle Jurassic Series.	Brown Jura, or Dogger.
	Lower Jurassic or Liassic Series.		

DISTRIBUTION OF JURASSIC ROCKS

American. — No undoubted Jurassic strata occur in the Atlantic border of the United States, though by some authorities the uppermost part of the estuarine Trias (*Newark* Series) is referred to this system, and by others the Potomac Series of the Cretaceous is regarded as Jurassic. Whether or not these references be correct, no marine Jura is known on the Atlantic slope of North America except in Mexico: in the latter country are some marine beds which probably belong to this system. In eastern North America the Jura was a time of great denudation, when the high ranges of the Appalachian Mountains were much wasted away, and the newly upheaved, tilted, and faulted beds of the Trias were deeply eroded.

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[1] The Malm is not quite the same as the White Jura, but includes some of the Brown, the remainder of which corresponds to the Dogger.

In the interior region of the continent the course of events was different. The Colorado island became joined to the mainland, forming a peninsula. In the great area from the Uinta Mountains southward to New Mexico and Arizona, and extending from the Colorado peninsula westward to the Great Basin land, was an interior sea or salt lake, in which were laid down great thicknesses of barren sandstone, without fossils. These beds are placed in the Jurassic entirely upon stratigraphic grounds, and whether they represent the whole Jura, or only a part, and if so, what part, are questions that cannot at present be answered. West of the Great Basin land, the Lias is found in California and Oregon, but not as yet in British Columbia, and recurs in several of the Arctic islands. The faunal relations of this Pacific border Lias are with that of central Europe.

The Middle Jurassic of North America is still very little known, but appears to have much the same distribution as the Lias.

In the upper Jura some extensive geographical changes occurred. Early in this epoch a depression was formed in the northern interior region, allowing the waters of the ocean to flow in and establish a gulf over portions of what had been the Triassic inland sea. The boundaries of this great gulf are not yet fully known, but it extended over the northern portion of Utah, where the Wasatch and Uinta Mountains now are, and covered most of Wyoming, as far east as the Black Hills, together with southern Montana. Although Jurassic exposures have not been found in Canada east of the Cordillera, yet the fossils of this gulf show that its waters were completely separated from those of California, which still retain their European connection, and were probably derived from a transgression from the north or northwest. The sediments deposited in the gulf are largely limestones, though with much clay shale and marl, while the presence of gypsum points to the existence of lagoons. The beds attain their maximum thickness of about 1800 feet in the Wasatch Mountains, which then formed the eastern coast of the Great Basin land. These strata have yielded many marine fossils, but the fossils are very scanty as compared with those of the beds formed in the open sea.

In the later part of the Jura, or upper Malm, still further changes were produced. In the Old World this was the time of a vast transgression of the sea, but in North America the land was rising, gradually drying up the great northern gulf, interrupting the connection with central European waters which had so long been shown by the fossils of the Pacific border, and bringing in a transgression of the Arctic Sea, which extended its waters all down the western coast of North America as far as Mexico, but was separated in some way from the sea which washed the west coast of South America. Upper Jurassic strata are found in British Columbia and California, where they form an enormously thick series, principally of slates, with interstratified beds of diabase tuffs, which show that volcanic activity prevailed along the shores, or in the bed of the sea. In the Sierra Nevada these slates are traversed by numerous gold-bearing quartz veins.

The close of the Jurassic was accompanied in North America by a time of upheaval and mountain making along the western side of the continent, corresponding to the Appalachian revolution which had occurred at the close of the Palæozoic era along the eastern side. The Sierra Nevada had for long ages been a sinking geosynclinal trough, in which great thicknesses of sediment had accumulated; now, at length, it yielded to the force of lateral compression, which ridged the strata up into great folds. By this movement the Pacific coast-line was transferred from the eastern to the western side of the mountains, and probably the Coast Range was upheaved, forming a chain of islands. Little is known concerning this primary condition of the Sierra Nevada, which had not yet become separated from the Great Basin by faults, the present mountains being due to long subsequent movements. In the interior of the continent also these movements brought about great changes, though it is not probable that the geographical modifications of the interior all occurred at the same time, or that they were all connected with the upheaval of the Sierra Nevada. We have already seen that marked changes were in progress during the upper Malm. The result of the diastrophic movements in the interior during the latter part, and at the close of the Jurassic period, was to drain the inland seas and the great northern gulf, converting nearly the whole region into land.

Foreign.—The greater part of South America was above the sea during the Jurassic period, as it had been in the Trias. Marine deposits of the former period are found only along the western border of the continent, where they extend from 5° to 35° S. lat. Throughout the Jurassic the sea which covered this western coast retained its faunal connection with the central European region, and even the minuter divisions, the substages and zones of the European Jura, are applicable to the classification of the South American beds. In what manner this southern area became separated from the Pacific border of North America in the upper Malm, it is difficult to conjecture.

In Europe the Jurassic rocks are magnificently displayed, but they differ much both in thickness and in character as they are traced from one country to another, which results from more frequent and more localized changes of level than had occurred during the Palæozoic.

The Lias has a much more restricted extension than the later Jurassic stages. At the end of the Triassic had begun a transgression of the sea, which flooded many of the inland basins and salt lakes, and the same transgression continued into the Lias, proceeding northward from the Mediterranean, and covering large areas in central and southern Europe, as well as a belt across England, but not extending to Russia. By far the greater part of the Eurasian land mass was above the sea, and fresh-water lakes extended across Siberia, while in China wide-spread deposits of Liassic coal were accumulated.

In the latter part of the middle Jura the transgression of the ocean was renewed, and this time on a vastly larger scale, cutting the continents by seas and straits, invading great areas that had long been land, and covering the larger part of Europe and Asia. This is one of the greatest transgressions of the sea in all recorded geological history, but it did not greatly affect North America. Central and northern Russia were invaded by an extension of the sea from the north, and in this Russian sea was developed a highly characteristic fauna. Strata distinguished by the Russian fauna extend through Siberia, Spitzbergen, Nova Zembla, Alaska, the Black Hills of South Dakota, and the uppermost Jurassic of California and Mexico. In peninsular India the Jura is represented by the upper division of the Gondwána system, which, as before, was laid down in an inland sea. The continental mass to which India then belonged was cut off from Asia by a strait or sea which covered the site of the Himalayas, but it may have been connected with Australia by way of the Malay islands, or, more likely, with South Africa. The great Jurassic transgression submerged considerable areas of northern India, as it also covered narrow areas along the eastern and western coasts of Australia. Much of Madagascar was under water, but the southern portion is believed to have formed part of the narrow land which extended from South Africa to India. Some of eastern Africa was covered by a bay of the Indian Ocean, but no marine Jurassic has been found in the southern or western portions of that continent.

The very striking faunal differences which obtain between different regions have led certain observers, especially the late Professor Neumayr of Vienna, to the conclusion that climatic zones had already been established in Jurassic times, — Boreal, central European, and Alpine or Equatorial zones, with corresponding ones in the Southern Hemisphere. This conclusion as to climatic belts is, however, a very doubtful one, and is in conflict with the distribution of the several geographical faunas, for the central European fauna is found in equatorial Africa, and the supposed equatorial fauna occurs in the Andes 20° of latitude south of its proper boundary. It is much more likely that the marked faunal differences are due to varying facies, depth of water, character of bottom, etc., and even more to the partly isolated sea-basins and the changing connections which were established between them. There is no cogent evidence to show that the Jurassic climate was less mild, equable, and uniform than that of preceding periods.

JURASSIC LIFE

The life of the Jurassic has been preserved in wonderful fulness and variety; but with comparatively few exceptions, our knowledge of it has been principally derived from Europe, where a host of eminent geologists have long studied the great wealth of material. The contrast between North America and Europe in regard to the relative abundance of Jurassic marine fossils is seen from the fact that while in Great Britain alone more than 4000 species have been described, in America hardly one-tenth of that number has so far been found.

Plants. — The flora of the Jurassic differs little, on the whole, from that of the Trias, and is made up of *Ferns*, *Horsetails*, *Cycads*, and *Conifers*. Tree ferns flourished in northern Europe in great variety. The Cycads attain their culmination of abundance and diversity in this period, no less than forty species occurring in a single horizon of the English Upper Jura; some of them, like *Palæozamia*, have leaves exceeding one foot in length. The Conifers are of somewhat more modern aspect than those of the Trias, and, from their resemblance to genera which are still extant, have received such names as *Thujites*, *Taxites*, *Cupressites*, *Pinites*, etc. The Araucarian pines still flourished in Europe. Monocotyledons have been reported from the Jurassic, but the evidence for their existence is very doubtful.

Foraminifera are found in great numbers and variety in the soft Jurassic clays, many of them belonging to genera which still abound in the modern seas. It must not be supposed that these organisms first became so abundant in Jurassic times; it is merely that the conditions for the preservation of these microscopic and exquisite shells had not been so favourable before.

Radiolaria. — The beautiful siliceous tests of the Radiolarians are also found in multitudes. In the Alps occur whole strata of red flints and jaspery slates, which are composed almost entirely of these tests.

Spongida. — Sponges are found in wonderful profusion and diversity and in such perfect preservation that every detail of their beautiful structure may be made out with the microscope. In some localities these sponges are heaped up in such masses that they fill the strata, while other localities of the same horizon are entirely free from them.

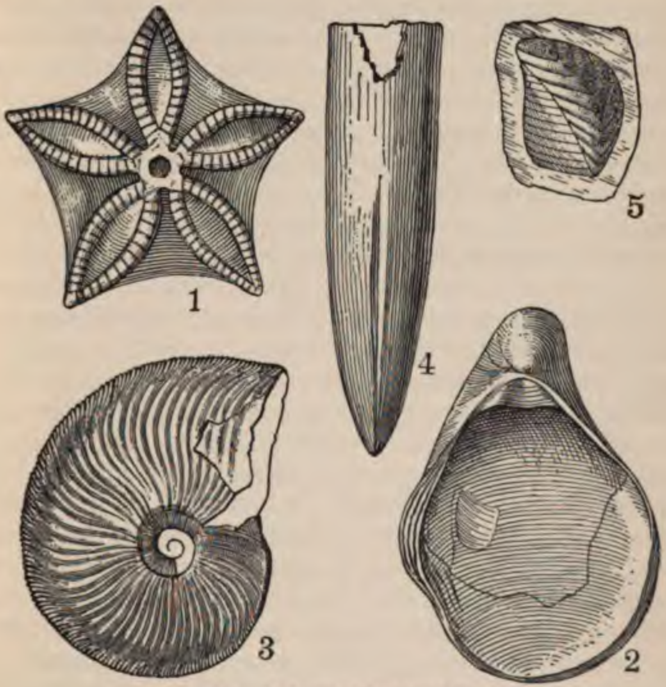

PLATE IX. AMERICAN JURASSIC FOSSILS

1. Segment of stem of Pentacrinus asteriscus, 4/1. 2. Gryphæa nebrascensis. 3. Quenstedioceras cordiforme, 2/3. 4. Belemnites densus, 2/3. 5. Trigonia americana. (After Meek and Hayden.)

Cœlenterata. — Corals abound, especially in the Upper Jurassic of central Europe. The *Anthozoan Corals* all belong to the modern *Hexacoralla*, in decided contrast to the Tetracoralla of the Palæozoic seas. *Isastræa*, *Montlivaultia*, and *Thecosmilia* are the dominant genera.

The **Echinodermata**, especially the Crinoids and Sea-urchins, are of great importance. The Crinoids are vastly more abundant than they had been in the Trias, and although the number of genera and species is not at all comparable to the great assemblage of Carboniferous time, yet for profusion and size of individuals the Jurassic has never been surpassed. Especially characteristic are the superb species of *Pentacrinus* (Pl. IX, Fig. 1), a genus which still exists in the West Indian seas. Other common genera are *Apiocrinus* and *Eugeniacrinus*. These genera all belong to the *Neocrinoidea*, which have a very different type of structure from the Palæozoic forms, but, like nearly all the latter, they were attached to the sea-bottom by their long stems. In the Jurassic first appear the free-swimming Crinoids, like *Comatula*, the commonest of modern genera. These animals possess a stem only in their early stages of development; subsequently they become detached and free. *Star-fishes* and *Brittle Stars* are not very common, but have attained a completely modern structure.

The *Echinoids* have undergone a wonderful expansion and diversification by the time of the Middle Jurassic. In the Lias, as in the Trias, we find only the regular, radially symmetrical sea-urchins, with mouth and anus at the opposite poles of the shell, but in the middle and upper Jura appear the irregular *Spatangoids* and *Clypeastroids*. In these the shell is bilaterally symmetrical, rather than radially so, the anus, and even the mouth, losing their polar positions, and the shape of the ambulacral areas being greatly changed. This is another instance of the attainment of modern structure which so many of the Mesozoic Invertebrates display.

Arthropoda. — The *Crustacea* are not found in very many localities, but places like the famous lithographic limestones of Solenhofen in Bavaria, where the conditions of preservation were favourable, show that this group was very abundant and far advanced in the Jurassic seas. The long-tailed (macrurous) Decapods (of which the lobster is a familiar example) are in the ascendant and are represented by many genera, several of which still exist. The Crabs, or short-tailed Decapods, which are now so very common, make their first known appearance in the Jurassic, but they were still rare, and connecting links between the long-tailed and short-tailed series were more abundant. *Isopods* and *Stomatopods* also abounded.

The *Limuloids* are reduced to the single genus *Limulus*, which then occurred in the European seas, while the living horseshoe crabs of that genus are found only on the east coast of the United States and in the Molucca Islands.

Spiders and *Centipedes* have not yet been found, — another illustration of the imperfection of the geological record. There can be no doubt that these animals existed in Jurassic times, for we find them both before and after that period.

Insects, on the other hand, are found in multitudes in certain localities, and display a great advance in the number of types over any of the Palæozoic periods. The Orthopters and Neuropters which we found in the Palæozoic are enriched by many new forms, such as grasshoppers and dragon-flies, while beetles (*Coleoptera*) become very abundant. The Hymenopters (ants, bees, wasps, etc.) and the Dipters (flies) date from the Jurassic, and Lepidopters (butterflies) have also been reported, though doubtfully. As the latter insects are dependent upon a flowering vegetation, definite proof of their presence in the Jura will establish the existence of the Angiosperms.

Brachiopoda. — These shells are still common in the Jura, but they are simply a profusion of individuals belonging to a few genera, most of which persist in our recent seas. *Terebratula*, *Waldheimia*, and *Rhynchonella* are much the most important genera, and the last stragglers of the long-lived Palæozoic *Spiriferina* are here found.

Mollusca. — The Bivalves, which had already become such important elements of the Triassic fauna, greatly increase in the Jura, their shells forming great banks and strata. Many of the genera are still living, and only a few of the more abundant ones can be mentioned here. Oysters like *Gryphæa* (IX, 2), *Exogyra*, and *Ostrea* itself are common. *Trigonia* (Fig. 151 and Pl. IX, Fig. 5) is especially characteristic of the Jura, but a few representatives of that genus have persisted to the present time and are found in the Australian seas. *Diceras* and *Pholadomya* are likewise common genera, and there are very many others. Among the *Gastropoda* the most significant change lies in the importance which the siphon-mouthed shells (*Siphonostomata*) now for the first time assume; examples of this group are *Nerinia*, *Alaria*, *Purpurina*, etc. Of the shells with entire mouths (*Holostomata*) the ancient Palæozoic genus *Pleurotomaria* is as abundant as ever, not beginning to decline until the Cretaceous period.

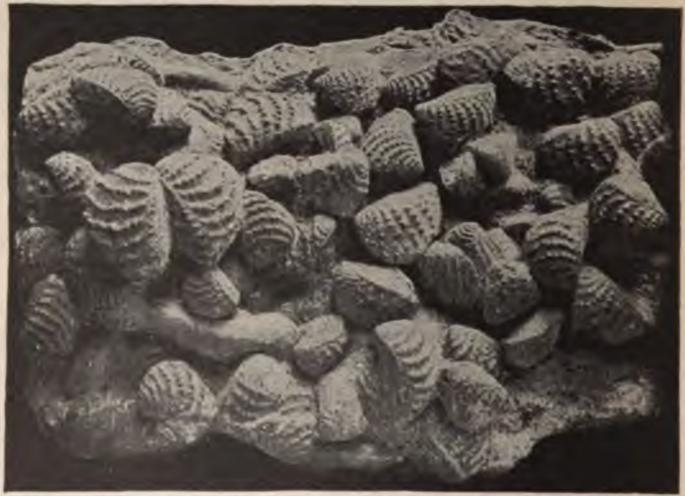

FIG. 151. — Slab of *Trigonia clavellata*, from the English Jura.

The *Cephalopods* are at the very height of their culmination, and are present in an astonishing profusion and diversity, filling whole strata with their heaped-up shells. The Nautiloids differ from those of the Trias in their smoother and more involute shells. The Ammonoids do not display so many types of shell structure as we have found in the Trias, and the genera are mostly different from those of the latter period; but in number of distinct species the Jura much surpasses the other Mesozoic periods. *Phylloceras* and *Lytoceras* continue on from the Trias, but the most abundant, characteristic, and widely spread genera are new. Of these may be mentioned: *Arietites*, *Ægoceras*, *Harpoceras*, *Stephanoceras*, *Perisphinctites*, and many others, each with large numbers of species. The *Belemnites*, which were introduced in a small way in the Trias, in the Jurassic blossom out into an incredible number of forms, exceeding even the Ammonites in abundance of individuals, if not of species. These extinct Cephalopods belonged to the *Dibranchiata*, as do all the living forms except the pearly Nautilus; they in some measure serve to connect the extinct genera having external shells with the existing naked squids and cuttle-fishes, which have only rudimentary internal shells, the pen or cuttle-bone. The *Belemnites* have a straight, conical, chambered shell, called the *phragmocone*, which ends above in a broad, thin plate. The phragmocone was partly external to the animal, and its lower, pointed end was inserted into a dart- or club-shaped body called the *guard* or *rostrum* (Pl. IX, Fig. 4), which is composed of dense, fibrous, crystalline calcite. Usually only the guard is preserved in the fossil state, and specimens are so common that they have attracted popular interest and bear the folk-name of "thunderbolts." In a few instances the animal has been preserved almost entire, so that the structure is well understood.

Vertebrata. — The *Fishes* have advanced much beyond those of the Trias. The Sharks have attained practically their modern condition, and the broad, flattened Rays are a new type of the order. The *Chimæroids* were much more numerous and relatively important than they are at present, when only a few are left. The Dipnoans have become very scarce and are hardly represented in the Northern Hemisphere, save for the persistence of *Ceratodus*. The Crossopterygians are greatly reduced, though a few exceedingly curious forms, like *Undina*, still linger. Of the Teleostome fishes the Ganoids are still the dominant type, as they had been since the Devonian. Some of these Jurassic forms are evidently the forerunners of the Sturgeons, but most of them resemble the Gar-pike of our Western rivers (*Lepidosteus*), and are covered with a heavy armour of thick, shining, rhomboidal scales. Many of these Ganoids are of small or moderate size, such as

Dapedius (Fig. 152) and *Aspidorhynchus* (Fig. 153), while others, like the superb *Lepidotus*, were very large, evidently the kings of their time and race. Some of the Jurassic fishes approximate the Teleosts so closely that it seems arbitrary to call them Ganoids. *Caturus*, *Leptolepis*, *Hypsocormus* (Fig. 154), and *Megalurus* are much like what the ancestral Teleosts must have been.

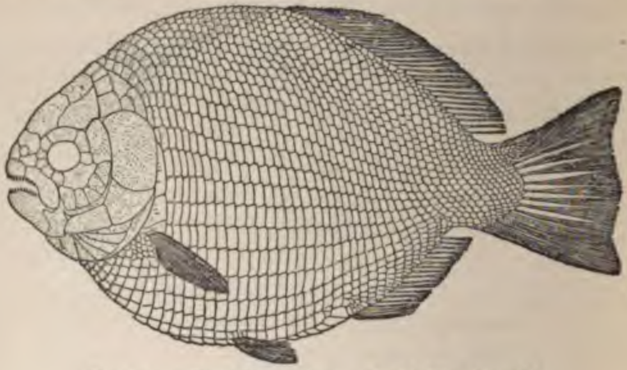

FIG. 152. — Dapedius politus. (Smith Woodward.)

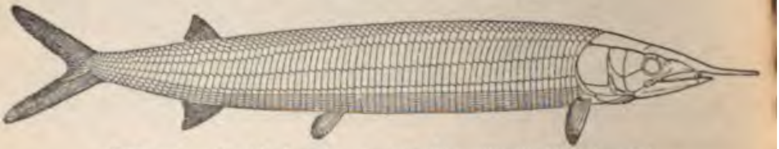

FIG. 153. — Aspidorhynchus acutirostris. (Smith Woodward.)

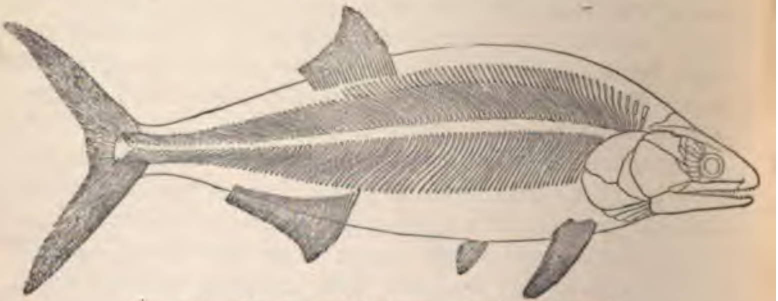

FIG. 154. — Hypsocormus insignis. (Smith Woodward.)

No *Amphibia* are certainly known from the Jurassic.

The *Reptiles* have attained a higher and more diversified plane of existence than in the Trias. Most of the Triassic genera and one entire reptilian order, the Theromorphs, have become extinct, but new and more advanced forms come in to take their places. The *Rhynchocephalians* continue and the first of the true *Lizards* (*Lacertilia*) appear. *Turtles* abound, having grown much more numerous than in the Trias. The *Ichthyosauria* are a highly characteristic Jurassic group; for though they are found in both the Trias and the Cretaceous, the Jura, and especially the Lias, is the time of their principal expansion. Certain localities in the Lias of England and Germany have yielded an incredible number of skeletons, and some of the specimens have preserved the impressions of the outline of the body and limbs, showing recognizably the nature of the skin. These reptiles were entirely marine in their habits and preyed upon fishes, and their limbs were converted into swimming paddles; there are several small dorsal fins and a large tail-fin, the principal organ of propulsion (see Fig. 155). The muzzle is drawn out into an elongate slender snout, armed with numerous sharp teeth, which were set in a continuous groove, not in separate sockets. The eye is very large and protected by a number of bony plates, which are often preserved in the fossil state. The neck is very short and hardly distinguished from the porpoise-like body. The skin was smooth, having neither horny scales nor bony scutes, which was of advantage in lessening the friction of the water. In length, these reptiles sometimes ex-

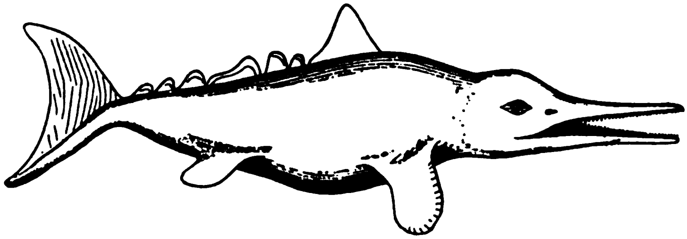

FIG. 155. — Restoration of *Ichthyosaurus quadriscissus*. (E. Fraas.)

ceeded 25 feet. *Baptanodon*, found in Wyoming, is an Ichthyosaur without teeth and must have fed upon small and soft marine invertebrates, as do the toothless whales.

Another group of carnivorous marine reptiles is that of the *Plesiosauria*, which began in the Trias and culminated in the Jura, and which forms a curious contrast to the Ichthyosaurs. In the typical genus *Plesiosaurus* (Fig. 156) the head is relatively very small, and the jaws are provided with large, sharp teeth, set in distinct sockets. The neck is exceedingly long, slender, and serpent-like, and marked off distinctly from the small body. The swimming paddles are much larger than in the Ichthyosaurs and probably had more to do with locomotion; the skeleton of the paddle departs much less widely from the structure of a terrestrial reptile's foot than does that of an Ichthyosaur. With their long necks, the Plesiosaurs could lie motionless far below the surface, occasionally raising their heads above the water to breathe, or darting them to the bottom after their prey, which consisted chiefly of fish. The Jurassic species of *Plesiosaurus* do not much exceed a length of 20 feet, but *Pliosaurus* of the same group was gigantic, a single paddle sometimes measuring 6 feet in length; the reptiles of the latter genus had, however, proportionately larger heads and shorter necks.

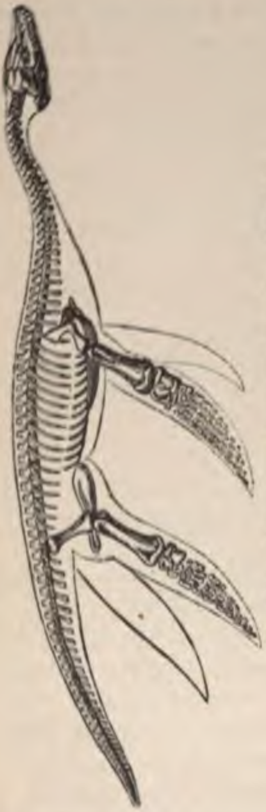

Fig. 156. — Plesiosaurus macrocephalus, $^1/_{20}$. (Owen.)

The seas and rivers of Jurassic times were swarming with *Crocodiles*, *Teleosaurus* being the characteristic genus of the period. In appearance these reptiles much resembled the modern Gavial of India and had a similar elongate and slender snout. The fore legs were much smaller than the hind, and these animals were doubtless of more exclusively aquatic habit than the crocodiles and alligators of the present day.

The *Dinosauria* have become much larger, more numerous and diversified than they had been in the Trias, though, as the footprints in the Newark sandstones teach us, only a small fraction of the Triassic Dinosaurs has yet been recovered. Making all due allowance for this, it seems, nevertheless, to be true that the group had made notable progress in the Jurassic. The group of Dinosauria is a heterogeneous one, comprising reptiles of very different size, appearance, structure, and habits of life. Some were heavy, slow-moving quadrupeds, having fore and hind legs of not very unequal length, with hoof-like toes, and usually with very small heads. Dinosaurs of this type were mostly plant-feeders and had rows of grinding teeth adapted for such a diet. *Cetiosaurus* is an example of this kind of Dinosaur, which attained a length of 40 feet. *Scelidosaurus* is another herbivorous reptile, but with such short fore legs that the gait must have been bipedal, or else the back must have been arched upward very strongly to the hind quarters. This animal, and its ally, *Omosaurus*, were provided with an armour of bony plates and spines covering the back and tail. *Megalosaurus*, on the other hand, was a gigantic carnivorous Dinosaur, having terrible, sharp-pointed teeth, while the toes were armed with sharp, curved claws. These creatures walked upon their elongated hind legs and were the most formidable beasts of prey that scourged the Jurassic lands. Not all of the Jurassic Dinosaurs were gigantic; very small ones also ranged through the forests or may even have been arboreal in their habits. *Compsognathus*, for example, was a bipedal, carnivorous Dinosaur hardly larger than a house cat.

Another very remarkable order of reptiles, the *Pterosauria*, appears for the first time in the Jurassic (Fig. 157). These animals were provided with wings, and were true fliers, thus realizing the old myth of flying dragons. The head is relatively large, but very lightly constructed, and set at right angles with the neck, as in birds. In the Jurassic species the jaws are more or less completely armed with teeth, which by their form show the carnivorous propensities of the animal. The joints of the external or little finger of the hand are much thickened and elongated, this finger being longer than the body and legs together. A membrane, or *patagium*, was stretched between the elongate finger on one side, and the body and leg on the other, thus forming the wing, which rather resembled the wing of the bat than that of a bird, though differing from the former in being supported by one finger instead of four. A few exceptionally well preserved specimens found in the Solenhofen limestones have retained the clearly-marked impressions of these wing membranes. The legs, like those of bats, were small and weak, and the tail was very short in some species, very long in others. Some, at least, of the latter had a membranous, oar-like expansion at the tip of the tail. That the Pterosaurs had the power of true flight, and did not merely take great leaps like the flying squirrels, is shown by the hollow, pneumatic bones (like those of birds), and by the keel on the breast-bone for the attachment of the great muscles of flight. This keel is found in both birds and bats. The skin was naked, having neither scales nor feathers. The Jurassic Pterosaurs were small, the spread of wings not exceeding 3 feet.

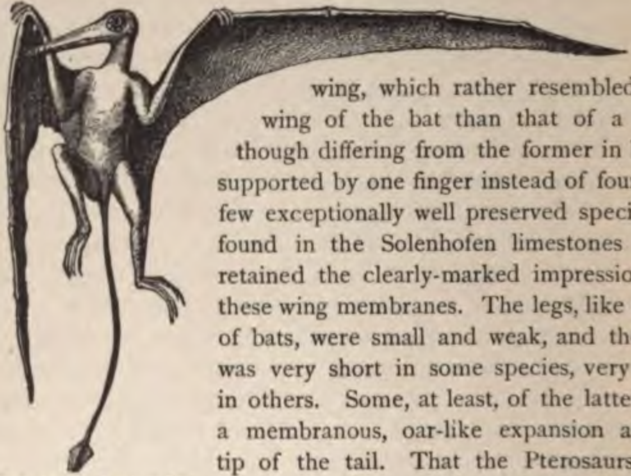
FIG. 157. — Restoration of Pterosaurian, *Rhamphorhynchus*. (Zittel.)

Birds. — One of the most remarkable advances which Jurassic life has to show consists in the first appearance of the birds. As yet, only a single kind of Jurassic bird has been found, and that in the Solenhofen limestones. This, the most ancient known bird, is called *Archæopteryx* (Fig. 158), and has many points of resemblance to the reptiles, and many characters which recur only in the embryos of modern birds. The peculiarities which strike one at the first glance are the head and tail; there was no horny beak, but the jaws are set with a row of small teeth, while the tail is very long, composed of separate vertebræ, and with a pair of quill feathers attached to each joint. The wing is constructed on the same plan as that of a modern bird, but is decidedly more primitive. The four fingers are all free (in recent birds two of them are fused together); they have the same number of joints as in the lizards, and are all provided with claws. The plumage is thoroughly bird-like in character, but is peculiar in the presence of quill feathers on the legs. This very extraordinary creature was, then, a true bird, but had retained many features of its reptilian ancestry, and shows us that those ancestors have still to be sought in the Trias or even the Permian.

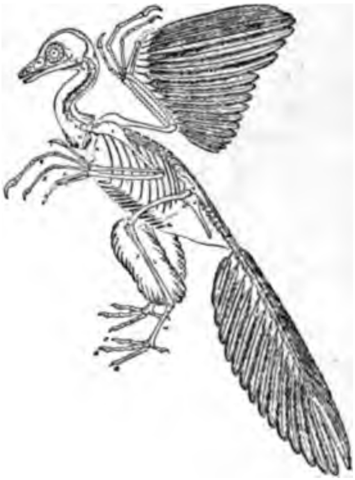

FIG. 158.— Restoration of *Archæopteryx macrura*. (Andreae.)

Mammalia. — The mammals of the Jurassic are still very rare and imperfectly known, and have been found in only a few places. How many mammalian genera should be referred to the Jurassic will depend upon where the somewhat arbitrary line is drawn, which separates that system from the Cretaceous. Excluding the transition beds of Wyoming and the Purbeck of England, three genera are known from the Jura, all found in European localities: *Phascolotherium*, *Amphitherium*, and *Stereognathus*, all of them tiny and very primitive creatures. From the scanty remains it is not possible to learn much about them.

CHAPTER XXX

THE CRETACEOUS PERIOD

THE name *Cretaceous* is derived from the Latin word for chalk (*Creta*), because in England, where the name was early used, the thick masses of chalk are the most conspicuous members of the system.

In very marked contrast to the scanty development of the Jura, the Cretaceous strata of North America are displayed on a vast scale, and cover enormous areas of the continent, eloquent witnesses of the great geographical changes in that long period. Fresh-water, estuarine, and marine rocks are all well represented, and, in consequence, our information regarding the life of North America and its seas during Cretaceous times is incomparably more complete than it is for the Triassic and Jurassic.

The Cretaceous rocks of North America are of very different character in the different parts of the continent, and require separate classification.

DISTRIBUTION OF CRETACEOUS ROCKS

American. — At the opening of the Cretaceous, the Atlantic coast of North America appears to have been farther to the eastward than it is at present; but just as had happened in the Triassic period, a long, narrow depression was formed, running roughly parallel with the coast, and in this depression one or more bodies of water accumulated, in which, for a long period of time, sediments in the form of sands and clays were deposited. This *Potomac* series, which is divisible into several stages, has been traced through the islands of Martha's Vineyard, Nantucket, Block Island, Long Island, Staten Island, across New Jersey, and

CRETACEOUS FORMATIONS OF THE UNITED STATES

	Atlantic Border	Gulf Border	Southern Interior	Northern Interior	Pacific Border
Upper Cretaceous	Manasquan-Rancocas Series.	Wanting.	Wanting.	5. Livingstone or Denver Stage.	
		Wanting.	4. Laramie Stage.	4. Laramie Stage.	Chico Series
	Monmouth-Matawan Series.	Ripley Stage. Upper Part of Rotten Limestone.	2. Glauconitic Beds. 1. Ponderosa Marls.	3. Montana Stage. 2. Fox Hills. 1. Fort Pierre.	
		Lower Rotten Limestone.	2. Austin Limestone. 1. Eagle Ford Shales.	2. Colorado Stage (Belly River). 2. Niobrara. 1. Benton.	
		? Upper Eutaw and Tombigbee.	Lower Cross Timber Sand.	1. Dakota Stage.	
Lower Cretaceous	Potomac Series 6. Albirupean or Raritan Stage. 5. Iron Ore Stage. 4. Acquia Creek Stage. 3. Mt. Vernon Stage. 2. Rappahannock Stage. 1. James River Stage.	Tuscaloosa (Alabama) and Eutaw (Mississippi).	Comanche Series 3 Washita Stage. 2. Fredericksburg Stage. 1. Trinity Stage.	Kootanie Stage. ? Como Stage.	Shasta Series Horsetown Stage. Knoxville Stage.

thence southward to Georgia, where it .turns northwestward, following the Mississippi embayment into Tennessee, and from there turning southwestward through Arkansas. In the northern part of this region, from Nantucket to the Delaware River, only the uppermost part of the Potomac series has been found. The Potomac is nowhere marine, and everywhere rests unconformably upon the underlying Triassic and older rocks. The accumulation of sediments in these depressions went on for a very long time, apparently throughout the whole of the Lower Cretaceous, and by some geologists it is believed that the process began in the Jurassic, to which period they refer the lowest members of the Potomac series. As the thickness of sediment is not great (not exceeding 600 feet), the process of deposition must have been very slow.

While along the Atlantic border the land was more extended than at present, in the southern part of the continent a different order of events was brought about. In southern Mexico occurred a depression which submerged the land almost from ocean to ocean, through probably leaving some sort of land barrier between the Atlantic and the Pacific. The transgression of the sea extended northward, covering most of Texas and Oklahoma, and sending a bay into southern Kansas. At the base of the Lower Cretaceous strata in Texas is found a deposit of fresh-water sands, the *Trinity* stage, which is the recognized equivalent of the basal Potomac. The advancing sea soon obliterated this body of fresh water, and the continued depression soon established a clear and quite deep sea, in which were formed the great masses of the *Comanche* limestones, that are the surface rocks of nearly all Mexico and cover a large part of Texas. The Ouachita Mountains of Arkansas stood out as a promontory in the Lower Cretaceous sea and the ancient shore line has been traced around their foot. Over much of Texas the Comanche limestones are soft, and beds of chalk occur among them; while in Mexico, where they have been folded into mountain ranges, they have become much harder and more compact. The thickness of the limestones increases southward; from 1000 feet in northern central Texas, it rises to 5000 feet on the Rio Grande, and on the Mexican plateau the almost incredible thickness of 10,000 to 20,000 feet has been reported. No less than six distinct, successive marine faunas are found in the Comanche limestones of Texas, and the faunal relationships of this region are closest with the Mediterranean province of Europe, and especially with the Lower Cretaceous of Portugal.

In the northern interior region the Lower Cretaceous beds were all laid down in inland bodies of water, part of which, at least, were fresh. One such body of water covered southern Wyoming, extending down the eastern flank of the Rocky Mountains into Colorado. In it were deposited a thin mass of sands and clays, the *Como Beds*,[1] in which are preserved the remains of a rich land fauna of reptiles and mammals. These beds are usually referred to the summit of the Jurassic, but their near equivalence seems to be with the Trinity of Texas, the basal Potomac of the Atlantic border, and with the English Wealden, all of which are well-nigh universally regarded as Cretaceous. Another non-marine and, at least locally, fresh body of water occurred east of the Gold Range of British Columbia, extending southward into Montana, and in it were deposited the sands and clays of the *Kootanie* stage, the plant remains of which correlate it with the lower Potomac, though it may have been considerably later than the Como beds. In this northern area there is no evidence of deep water, but only of shallow seas or lakes, with tracts of low-lying, swampy lands, on which a luxuriant vegetation produced valuable deposits of coal. Other inland waters occupied an unknown extent of the Great Plains area; Lower Cretaceous beds have been found surrounding the Black Hills and in a few other localities.

Along the Pacific coast Lower Cretaceous rocks are displayed on a great scale. The Great Basin land then extended from southern Nevada to latitude 54° N. in British Columbia, with the Sierra Nevada rising along part of its western shore, to which the Pacific extended. North of the Gold Range in British Columbia, the ocean spread eastward, though no doubt broken by many islands, to the eastern base of the Rocky Mountains. The Coast Range of California formed a chain of islands and reefs. In the Sierra Nevada occurs an unconformity between the ·Lower Cretaceous and the uppermost Jurassic, but it does not imply the lapse of a very long period of time.

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[1] These beds were named by their describer, Professor Marsh, the *Atlantosaurus Beds*, but as this name is inadmissible, the term *Como Stage* may be substituted, from Como, Wyoming, the typical locality.

The older division of the Californian Lower Cretaceous is called the *Knoxville*, and has an estimated maximum thickness of 20,000 feet, laid down upon a slowly subsiding sea-bottom. At the end of the Knoxville age, the subsidence became more rapid and the sea began to encroach upon the land, for the *Horsetown* beds, which have a thickness of 6000 feet, overlap the Knoxville shoreward and extend over upon the underlying Jurassic and other pre-Cretaceous systems. Although the two stages of the Californian Lower Cretaceous are entirely conformable throughout, and appear to have been formed by a continuous process of sedimentation, yet there is a very marked faunal change between them. The Knoxville beds have a northern fauna, allied to that of Russia, showing that the connection with Russian seas, which had been established in late Jurassic times, was still kept up. With the beginning of the Horsetown age, however, this northern communication was interrupted, and a connection was formed with the waters of southern Asia, and in that way with central Europe. The decided contrast which we find between the Lower Cretaceous faunas of California and of Texas points to the existence of a land barrier between the seas of the two regions.

In the southern region the Lower Cretaceous was terminated by a great upheaval, which over most of Mexico and Texas caused the ocean to retire nearly to its present position, raising at the same time a long ridge of land which became connected with the Great Basin land. This mid-Cretaceous land epoch must have continued for a considerable time, permitting extensive denudation and a complete change in the fauna. Wherever the Upper Cretaceous is in contact with the Comanche limestones, the two are unconformable, and no species of animal is known to pass from one to the other. These limestones form the principal mass of the Mexican mountains, where the force of compression has converted them into rocks of great density, and from their ancient appearance they were long supposed to be Carboniferous.

The Upper Cretaceous rocks have a far wider distribution over North America than have those of the lower division, which is due to an enormous transgression of the sea over the land, one of the greatest in all recorded geological history. Over the region of the Great Plains the Upper Cretaceous was inaugurated by the formation of a non-marine stage, the *Dakota.* These strata cover much of Texas, lying unconformably upon the Comanche series, and extend northward into Canada. It is very difficult to comprehend under what conditions these vast sheets of conglomerate and sandstone could have been laid down, and there is much reason to believe that not all the beds referred to the Dakota really belong to it. On the western side of the Colorado uplift, the Dakota is less distinctly a sandstone formation, and is characterized by beds of shale and even coal seams of workable thickness. In most parts of the Rocky Mountain region the Dakota rests in apparent conformity upon the lowest fresh-water Cretaceous, and even upon the Jurassic. In the Uinta and Wasatch ranges there is no apparent break in sedimentation from the Palæozoic to the end of the Cretaceous, though the whole Lower Cretaceous is there wanting. From this we may infer that during the long Lower Cretaceous time all these regions had been low-lying lands, nearly or quite at base-level, and therefore not subject to profound denudation.

It was at the end of the Dakota age that the great subsidence took place which affected nearly all parts of the continent, and brought the sea in over vast areas where for ages had been dry land. South of New England the Atlantic coastal plain was submerged, and in New Jersey, at least, the waters covered even the Triassic belt, bringing the sea up to the foot of the crystalline highlands. The lowlands of Maryland, Virginia, and the Carolinas, and all of Florida were under the ocean, and the Gulf of Mexico was extended northward in a great bay (the Mississippi embayment), covering western Tennessee and Kentucky and extending into southern Illinois. Northeastern Mexico and Texas were again submerged, and a wide sea connected the Gulf of Mexico with the Arctic Ocean. The eastern coast of this interior sea began in northwestern Texas, running through Kansas and Iowa nearly to the present line of the Mississippi River. Westward the coast-line was the uplift which ran from southern Mexico into British Columbia. The Colorado region was again converted into islands. North of the Great Basin land the interior sea was connected with the Pacific and Arctic Oceans, which united over the northwestern part of the continent.

On the Pacific side, the Sierras, which had suffered greatly from denudation, were again folded, and separated from the interior basin by a fault, while a fracturing of the crust began the system of Basin Ranges, arching upward the surface of the Great Basin. A moderate transgression of the sea caused the Upper Cretaceous to extend farther east than the Lower. Volcanic activity continued and immense bathyliths were formed deep within the mountains. The sea extended from Lower California northward along the Sierra, into eastern Oregon at the foot of the Blue Mountains.

The North American continent was thus divided into two principal land masses, the larger one to the east and comprising the pre-Cambrian and Palæozoic areas. In the limits of the United States this land lay almost entirely east of the Mississippi, except for a southwestern peninsula, including Missouri, Arkansas, Oklahoma, and part of Texas. The western area was much smaller, extending from southern Mexico into British Columbia, and having its greatest width between the fortieth and forty-fifth parallels of latitude. Between the two lands lay the Colorado islands, and doubtless many smaller ones as well.

The character of sedimentation differed so much in the various regions of the continent that the subdivisions of the Upper Cretaceous have received different names in the separate provinces, and only approximately correspond in time.

Along the Atlantic border the Upper Cretaceous strata are a series of marine sands and clays, which are still almost horizontal in position and of loose, incoherent texture. In New Jersey there are extensive developments of green sands (see p. 175), locally called marl. The Appalachian Mountains, which had been subjected to the long-continued denudation of Triassic, Jurassic, and Lower Cretaceous times, were now reduced nearly to base-level, the Kittatinny plain of geographers (see p. 342). This peneplain was low and flat, covering the whole Appalachian region, and the only high hills upon it were the mountains of western North Carolina, then much lower than now. Across this low plain the Delaware, Susquehanna, and Potomac must have held very much their present courses, meandering through alluvial flats.

On the Gulf border the Upper Cretaceous beds of Alabama and Mississippi are limestones called the *Rotten Limestone* below (500 to 1200 feet thick), and the *Ripley* above (200 feet). Eastward the water shallowed, and in Georgia we find about 1400 feet of clays and sands. Northward along the Mississippi embayment the beds thin greatly and are mostly clays and sands.

In the interior region lying upon the Dakota are the marine beds of the *Colorado*, of which the lower division is the *Benton*, a mass of shales and limestones with a maximum thickness of 1000 feet, though varying much from point to point. The depression still continuing, the sea became quite deep, making favourable conditions for the formation of the chalk and harder limestones of the *Niobrara*. This chalk is best seen in Kansas, but extends into South Dakota; elsewhere are sandstones and limestones with a maximum thickness of 2000 feet. A movement of reëlevation of the sea-bottom began even in Colorado times, and in the northern part of the interior region oscillations of level produced alternating fresh-water, or estuarine, and marine conditions. In Montana and the Canadian province of Alberta is a thick body of estuarine or fresh-water strata with seams of coal (the *Belly River* formation) interposed between the marine deposits of the Colorado below and the Montana above. In Utah is another fresh-water deposit of coal-bearing rocks of Colorado age.

In the *Montana* stage marine conditions still prevailed, but the waters of the northern sea had generally become much shallower, and a marked change of fauna is produced. In Alberta are coal measures of this date. Two divisions of the Montana are distinguished, although not everywhere separable; the *Fort Pierre*, which is composed of shales and sandstones with a maximum thickness of 8000 feet, and the *Fox Hills*, sandstones and some shales, which do not exceed 1000 feet. This movement of upheaval in the interior was accompanied or followed by an uplift on the Atlantic and Gulf coasts, for along these borders the uppermost Cretaceous beds are either wanting or represented by exceedingly thin deposits. In the interior the continued upheaval caused estuarine, fresh-water, and swampy conditions to prevail over very wide areas, though not so widely extended as had been the Upper Cretaceous sea. The older part of this great fresh- and brackish-water formation is the *Laramie*. The northwestern part of the continent had been converted into dry land, but a broad estuary extended up the course of the present Mackenzie River to latitude 62° N. Another and vastly larger body of water began about latitude 57° N. and reached, though perhaps with interruptions, to northeastern Mexico, surrounding the Colorado island. This great inland sea was 2000 miles long and 500 miles wide, though it is by no means certain that all of it was under water at the same time. In the swamps and shallows were gathered great quantities of vegetable matter, now converted into coal seams. Workable coal is found in all the stages of the western Cretaceous, but none of these stages is comparable to the Laramie for the extent and thickness of its coal measures. In the Laramie sea were alternating conditions of fresh and brackish water and, it is said, occasional inroads from the ocean occurred.

The Laramie was a time of tranquillity, with only slow and gentle changes of level, but towards its close some important disturbances took place, especially along the Rocky Mountains. The first of these movements affected only the Colorado island, and its effects are especially well shown in the Denver basin, where some 800 feet of conglomerates (the *Arapahoe*) rest upon the Laramie unconformably. The second series of movements was much more extensively felt, producing marked unconformities both in Colorado and Montana. In Colorado there was a great volcanic outburst, and the *Denver* stage, which overlies the Arapahoe unconformably, is principally composed of andesitic tuffs. In Montana the equivalent stage (*Livingstone*) is 7000 feet thick and unconformable with the Laramie.

The Upper Cretaceous of the Pacific coast comprises the *Chico* series, with a maximum thickness of 4000 feet. In Vancouver's Island the Chico is coal-bearing. The faunal connections of the Chico are with southern Asia, that series having very little in common with those of the interior region. The uppermost Cretaceous is wanting along the Pacific coast, except for certain coal-bearing beds in Washington, which appear to represent the Laramie.

The Mesozoic era was closed in the West, as the Palæozoic had been in the East, by a time of great mountain making, and to this movement is attributed the formation of most of the great Western mountain chains. From the Arctic Ocean far into Mexico the effects of the disturbance were apparent. The Rocky Mountains, the Wasatch and Uinta ranges, the high plateaus of Utah and Arizona, and the mountains of western Texas and Mexico date from this time, though subsequent movements have greatly modified them. Vast volcanic disturbances accompanied the upheaval, which was on a far grander scale than the Appalachian revolution.

Foreign. — In South America the Cretaceous history is much like that of the northern continent. The subsidence which inaugurated the Lower Cretaceous extended the sea over the northern part of South America and covered northeastern Brazil, with fresh-water deposits in central Brazil. All along the Cordillera, from Venezuela to Patagonia, marine Cretaceous is found, but east of the mountains, with the exceptions already noted, the system is represented chiefly by non-marine sandstones. The faunal relations of the South American Lower Cretaceous are very intimate with northern and western Africa. Gigantic volcanic activity went on along the Cordillera in Mesozoic times; in Chili and Peru the marine Cretaceous is principally made up of stratified igneous material, and the Andes contain the largest known area of Mesozoic eruptives. The mountain-making upheaval probably came at the close of the Cretaceous.

In Europe, toward the end of the Jura, the sea retired from nearly all of the central region, which in part became dry land and in part was covered with lakes and inland seas. One of the largest of these covered much of southern England, extending far into Germany, and in it was deposited a great thickness of sand and clay, with some shell limestone, the *Wealden*. The Alpine region remained submerged under a clear and deep sea, and the transition from the Jurassic is very gradual. In the oldest Cretaceous epoch (*Neocomian*) a renewed transgression submerged large parts of central Europe, though the sea was far less extensive than that of the Middle and Upper Jurassic. In consequence, a great gulf was established over southern England, northern France, and north Germany to Poland, a gulf bounded on the north by the highlands of Britain, Scandinavia, and northwestern Russia, and on the south by a land stretching from Ireland to Bohemia; Belgium was an island. The expanded Mediterranean covered southeastern Asia Minor and northern Africa. In the Upper Cretaceous the northern gulf was greatly extended, covering many areas that had been land since Palæozoic or pre-Cambrian times. Parts of this basin became very deep, and its most characteristic deposit, especially over southern England and northern France, was chalk, which the microscope shows to be made up of the shells of Foraminifera and to greatly resemble the modern foraminiferal oozes (see p. 215). Over the Alpine region upheavals in the Upper Cretaceous had established land areas, indicated by extensive fresh-water deposits, recurring at intervals from Spain to Hungary, in the latter country containing coal. The Cretaceous was closed in Europe by a gradual upheaval which excluded the sea from wide areas that it had occupied.

In Africa the only extensive Cretaceous areas are those of the north, where the Atlas Mountains and much of the surface of the Libyan desert are made up of these rocks. A limited transgression of the sea also took place along the western coast and another on the east coast of Cape Colony and Natal.

Southern and eastern Asia display many areas of Cretaceous rocks, as, for example, in southern India and Japan. Australia lso has extensive areas of this system, which are best known in

Queensland, where they are chiefly Lower Cretaceous and contain coal. The New Zealand Cretaceous is also coal-bearing.

CRETACEOUS LIFE

The life of the Cretaceous displays so great an advance over that of the Jurassic that the change may fairly be called a revolution.

Plants. — If the separation between the Mesozoic and Cenozoic eras were made entirely with reference to the plants, it would pass between the Jurassic and the Cretaceous, just as a similar criterion would remove the Upper Permian to the Meozoic (see p. 432). The vegetation of the Lower Cretaceous, especially of the lowest, is still much like that of the Jura. Ferns, Horsetails, Cycads, and Conifers continue to make up most of the flora, but the impending revolution is announced by the appearance of *Dicotyledons* of archaic and primitive type. In the higher parts of the Potomac the Cycads become much less abundant and the Dicotyledons very much more so. Here we find many leaves which belong to genera that cannot be distinguished from those of modern forest trees, such as *Sassafras*, *Populus*, *Liriodendron*, etc. No Dicotyledons

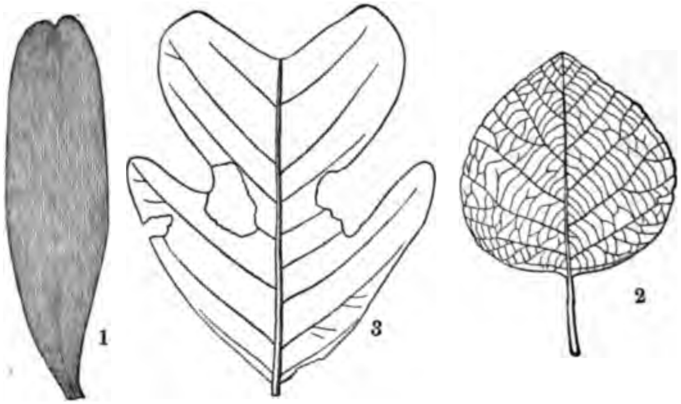

FIG. 159. — Cretaceous leaves, Dakota stage. 1. Dammarites emarginatus, 1/2. 2. Betulites Westi, 3/4. 3. Liriodendron giganteum, 1/2. (After Lesquereux.)

have been found in the Kootanie of the Northwest, or in the Wealden of northern Europe, but they occur in the Lower Cretaceous of Portugal. In the latter part of the Lower and in all the Upper Cretaceous, the flora assumes an almost completely modern character, and nearly all of our common kinds of forest trees are represented: Sassafras, Poplars, Willows, Oaks, Maples, Elms, Beeches, Chestnuts, and very many others. A new element is the Monocotyledonous group of Palms, which speedily assume

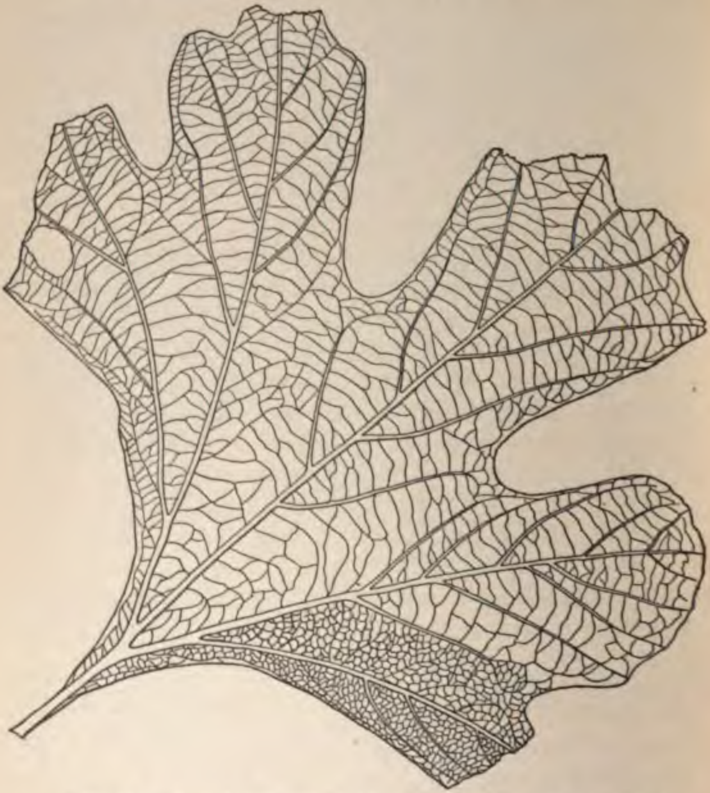

FIG. 160.—Sassafras dissectum, 1/2. Dakota stage. (Lesquereux.)

great importance. Each successive plant-bearing horizon of the Cretaceous is characterized by its own special assemblage of plants, but in its general features the Upper Cretaceous flora is essentially modern. Cretaceous *animals* are sufficiently different from those of the Jura, but the change is not so revolutionary as we have found among the plants.

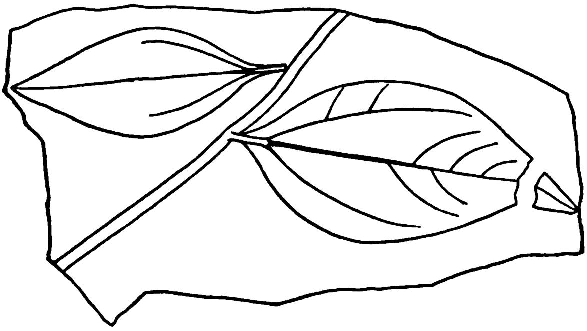

FIG. 161.—Cinnamomum affine, 1/2. Laramie stage. (Lesquereux.)

Foraminifera play an important part in the construction of Cretaceous rocks, especially of the great masses of chalk, while the green sands are casts of foraminiferal shells in glauconite. The most abundant genus, as in the recent Atlantic oozes, is *Globigerina*.

Spongida. — In the Cretaceous of Europe Sponges are more numerous and varied than at any other time, but in North America they are far less common.

Cœlenterata. —The Corals were very much as they are to-day and require no special description.

The **Echinodermata** undergo some very marked changes. The Crinoids are much reduced since the Jurassic, and never again assume their ancient importance; characteristic Cretaceous genera are the stemless *Uintacrinus* (Pl. X, Fig. 1) and *Marsupites*. The Sea-urchins are incomparably more numerous in Europe than in North America; of the Regular forms may be mentioned *Pseudodiadema* (X, 2), *Cidaris*, and *Salenia*, and of the Irregular forms, *Toxaster* (X, 3), *Holaster*, *Cassidulus*, etc.

Arthropoda. — Among the Crustacea we need only note the great increase in the Brachyuran Decapods, or Crabs.

Brachiopoda are very much as in the Jurassic; the common genera are *Terebratula* (X, 4), *Terebratella* (X, 5), and *Rhynchonella*.

Mollusca. — This group is very richly developed and many genera are peculiar to the period. The large, curious oysters belonging to the genera *Ostrea* (X, 6), *Gryphæa*, and especially *Exogyra*, are common, and the many species of *Inoceramus* (X, 7) are very characteristic. Confined to the Cretaceous are the extraordinary shells classed as *Rudistes*, in which one valve is long and horn-shaped, and the other a mere cover for it. These shells of the genera *Hippurites*, *Radiolites*, and *Coralliochama* are much commoner in Europe than in America. Other peculiar Cretaceous Bivalves are *Requienia*, *Caprotina* (X, 8), and *Aucella* (X, 18), the latter also Jurassic. The *Gastropods* (Pl. X, Figs. 9, 10, 11), are very much as in the Jura, but in the latter part of the period come in many genera which reach their fullest development in Tertiary and recent times, such as *Fusus*, *Murex*, *Voluta*, *Cypræa*, and many others.

The *Cephalopods* are very peculiar; in addition to numerous Ammonoid genera with closely coiled shells of normal type, such as *Hoplites*, *Schlœnbachia*, *Placenticeras*, we find very many shells entirely or partially uncoiled, or rolled up in peculiar ways, which give to the Cretaceous Cephalopod fauna a character all its own. In *Crioceras* the shell is coiled in an open, flat spiral, the whorls of which are not in contact. *Ancyloceras* has a similar open coil, followed by a long, straight portion, and recurved ter-

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Explanation of Plate X, p. 489. 1. Uintacrinus socialis, 1/12. (Clark). 2. Pseudodiadema texanum. (Clark.) 3. Toxaster texanus. (Conrad.) 4. Terebratula Harlani, 3/4. (Whitfield.) 5. Terebratella plicata. (Whitfield.) 6. Ostrea larva. (Whitfield.) 7. Inoceramus problematicus, 3/4. (Meek.) 8. Caprotina bicornis, 1/3. (Meek.) 9. Fasciolaria buccinoides. (Meek.) 10. Anchura americana. (Meek.) 11. Margarita nebrascensis. (Meek.) 12. Ptychoceras Mortoni, 3/4. (Meek.) 13. Scaphites nodosus, 1/2. 14. Baculites compressus, 1/2. (Meek.) 15. Belemnitella americana, 1/2. (Whitfield.) 16. Nodosaria texana, enlarged. (Conrad.) 17. Micrabacia americana, 3/1. (Meek.) 18. Aucella Piochi. (Gabb.)

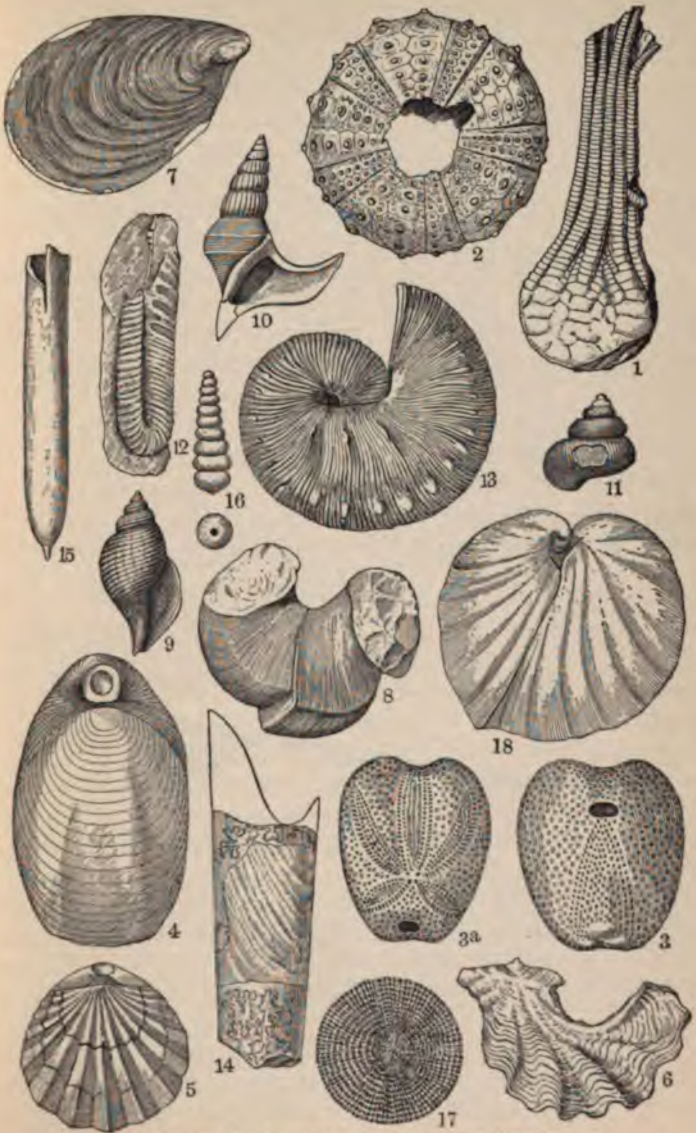

PLATE X. AMERICAN CRETACEOUS FOSSILS

minal chamber. *Scaphites* (X, 13) is like a shortened *Ancyloceras.* In *Ptychoceras* (X, 12) the shell consists of two parallel parts, connected by a single sharp bend. *Turrilites* is coiled into a high spiral, like a Gastropod, and *Baculites* (X, 14) has a perfectly straight shell except for a minute coil at one end. *Nautilus* is represented by many species, some of them very large. Belemnites are very abundant, but in the Upper Cretaceous the genus *Belemnitella* (X, 15) replaces the true *Belemnites.*

The **Vertebrata** form the most characteristic element of the Cretaceous fauna. Among the *Fishes* a revolution has occurred. Sharks of modern type abound, and their teeth are found in countless numbers; but the principal change consists in the immense expansion of the *Teleosts* or Bony Fishes, which now take the dominant place, while Ganoids become rare. Most of the Cretaceous Teleosts belong to modern families and even genera, such as the Herrings, Cod, Salmon, Mullets, Catfishes, etc.; but a characteristic Cretaceous type, now extinct, is that of the *Saurodonts,* fierce, carnivorous fishes of great size and power. The genus *Portheus,* common in the Kansas chalk, was 12 to 15 feet long, and was provided with great, reptile-like teeth.

The *Reptiles* continued to be the dominant types of the land, the sea, and the air, and it may fairly be questioned whether the Jura or the Cretaceous should be regarded as the culminating period of Reptilian history. *Ichthyosaurs* and *Plesiosaurs* are perhaps less abundant than in the Jura, but are of greatly increased size. *Elasmosaurus,* a Plesiosaur from the Kansas chalk, had a length of 40 to 50 feet, of which 22 feet belonged to the slender neck. Confined to the Cretaceous are the remarkable marine reptiles of the group *Pythonomorpha,* or *Mosasauria,* which swarmed on the Atlantic and Gulf coasts, and especially in the

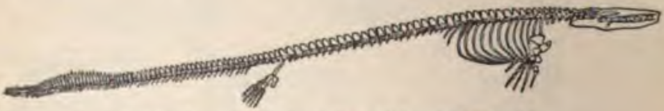

FIG. 162. — Clidastes velox, 1/96. (Williston.)

interior sea. These were gigantic, carnivorous marine lizards, with the limbs converted into swimming paddles (see Fig. 162). *Turtles*, both fresh-water and marine, abound, and some were very large. *Lizards* and *Snakes* are but scantily represented, not displaying the manifold variety of structure which they afterwards acquired. *Crocodiles*, like those of modern days, were ubiquitous in both fresh and salt waters.

The *Pterosaurs* of the Cretaceous are remarkable for their great size, far exceeding that of the Jurassic species. *Ornithostoma*, which has been found both in Kansas and in Europe, had a head of nearly 3 feet in length, with a long, pointed, toothless bill, like that of a bird; the spread of wings exceeded 20 feet.

The *Dinosaurs* continue in even greater profusion than in the Jurassic; they are, of course, much commoner and better preserved in fresh-water deposits than in marine, and hence are best known from the base and the summit of the system. Many of the genera were the largest land animals that ever lived, and the size of the bones is astonishing. *Ornithopsis*, *Diplodocus*, and *Cetiosaurus* are examples of immense, quadrupedal herbivorous Dinosaurs. In *Stegosaurus* the shortness of the fore limbs gives the back a very strong curvature; this remarkable genus had a defensive armour of enormous bony plates and spines, extending in the middle line of the back from the head to the end of the tail. *Camptosaurus* was also herbivorous, but had an erect bipedal gait. *Megalosaurus* was a carnivorous reptile, with huge teeth and a nasal horn; its fore legs are very small and its gait was erect. These genera and others are all found in the Como beds (which may be Jurassic), and very similar ones occur in the Trinity and lower part of the Potomac, as also in the Wealden of Europe. Especially famous is the genus *Iguanodon*, of which many complete skeletons have been found in Belgium. Dinosaurs are much less common in the marine Upper Cretaceous, but the green sands of New Jersey have yielded *Hadrosaurus*, an herbivorous Dinosaur much like *Iguanodon*, and some carnivorous types also. The Laramie and Denver beds have preserved many fine specimens, which show that the Dinosaurs flourished in almost undiminished variety till the end of the Cretaceous. The erect, herbivorous type is represented in these beds by *Monoclonius* and *Diclonius* (Fig. 164), which are nearly related to *Hadrosaurus*. *Agathaumas* (Fig. 163) and *Torosaurus* are huge, quadrupedal reptiles, with three large horns on the head and an extraordinary frill-like extension of the skull over the neck. Carnivorous Dinosaurs likewise continued, such as *Lælaps* and *Ornithomimus*, the latter with hind limbs which are especially birdlike in structure.

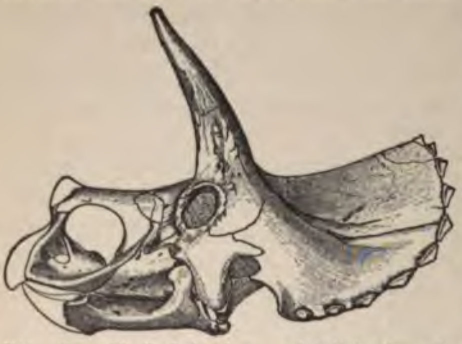

FIG. 163.—Skull of *Agathaumas flabellatus*, from the side, 1/30. (Marsh.)

The *Birds* of the Cretaceous are much more abundant and advanced than the known Jurassic birds. In the Upper Cretaceous of Kansas, and probably of England also, are found two remarkable birds, *Hesperornis* and *Ichthyornis*. In the former, which was nearly 6 feet high, the wings were rudimentary, while *Ichthyornis*, a much smaller bird, had powerful wings. Both of these genera possessed teeth, like *Archæopteryx*, but except in that feature and in certain minor details of structure, they are entirely like modern birds. Bird bones, like the corresponding parts of the Cormorants and Waders, have been found in the green sands of New Jersey, but it is not known whether they had teeth.

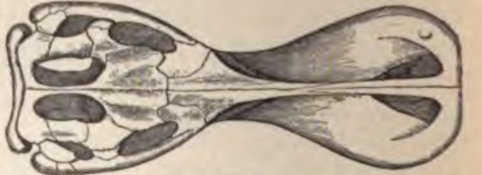

FIG. 164.—Skull of *Diclonius mirabilis*, from above, 1/19. (Cope.)

Mammalia.—Cretaceous Mammals are much more numerous and varied than those of the Jurassic, but they continue to play a very modest rôle, and are nearly all of minute size. In America they have been found only in the fresh-water beds at the base and summit of the Cretaceous, and in Europe only in the Purbeck and Wealden at the base. The Lower Cretaceous mammals differ little from those of the Jura (except for the larger number of genera), and from the fragmentary condition of the specimens it is exceedingly difficult to determine just what groups are represented. The *Multituberculata* are believed to belong to the lowest type of mammals, the *Monotremata*, at present represented only by the Spiny Ant-eater (*Echidna*) and Duck-billed Mole (*Ornithorhynchus*) of Australia. Of this group the most prominent Lower Cretaceous genera are the English *Plagiaulax* and the American *Ctenacodon* and *Allodon*. In another group the teeth are much simpler but more numerous; examples are *Stylodon* and *Triconodon* from the English Purbeck, and *Dryolestes* and *Dicrocynodon* from Wyoming. In the uppermost Cretaceous the mammals are much more numerous and diversified, and already begin to show affinities with the forms which are to succeed them in the Tertiary. The *Multituberculata* are represented by two genera, *Meniscoëssus* and *Ptilodus*, while other mammals of doubtful affinities are *Didelphops*, *Pediomys*, and *Cimolestes*. Many others are known, but they are too imperfect for reference. With one exception, *Thlæodon*, which is of moderate size, all these mammals are exceedingly small.

In brief, Cretaceous life is still typically Mesozoic, but a change toward Cenozoic conditions is already manifest, especially in the Plants, the Gastropods, and the Teleostean Fishes. There is still a gap between the life systems of the two eras, but it is not so wide as it was once believed to be, and it may be hoped that future discoveries will bridge it entirely.

CHAPTER XXXI

CENOZOIC ERA — TERTIARY PERIOD

The history of the Cenozoic era brings us by gradual steps to the present order of things. Of no part of geological history have such full and diversified records been preserved as of the Cenozoic, and yet this very fulness is a source of difficulty and embarrassment when we attempt to arrange the various phenomena in their chronological order.

The sedimentary rocks of the Cenozoic era are, for the most part, quite loose and uncompacted; it is relatively rare to find hard rocks, such as so generally characterize the older formations. They are also most frequently undisturbed, retaining nearly their original horizontal positions, except when they have been upturned in the formation of great mountain chains. Another characteristic feature of Cenozoic strata is their locally restricted range; only in the oldest parts of the group do we find such widely extended formations as are common in the Palæozoic and Mesozoic groups, and the later Cenozoic strata become more and more local in their character.

The *climate* of the era underwent some very remarkable and inexplicable changes. At the beginning it resembled that of the Cretaceous in its generally mild and equable character, a luxuriant vegetation flourishing far within the Arctic Circle; but by very slow gradations the climate grew colder, culminating in the Glacial Age, when much of the land in the Northern Hemisphere was covered with sheets of ice and snow and reduced to the condition of modern Greenland.

The *life* of the Cenozoic era is very clearly demarcated from that of the Mesozoic, though many modern characteristics began in the Cretaceous or even earlier. The peculiar Mesozoic Ammonoids, Belemnites, and many curious Bivalves disappeared almost entirely at the end of the Cretaceous, leaving only a few stragglers here and there to persist into the older Tertiary. Even more striking is the dwindling of the Reptiles; the Ichthyosaurs, Plesiosaurs, Pythonomorphs, Dinosaurs, and Pterosaurs, which had given such a marked individuality to the Mesozoic fauna, have become totally extinct, leaving only Lizards and Snakes, Turtles and Crocodiles, to represent the class. But Cenozoic life is not distinguished from Mesozoic merely by negative characters; it has its positive features as well. The plants and invertebrated animals nearly all belong to *genera* which are still living, and the proportion of modern *species* steadily increases as we approximate the present time. The Fishes, Amphibia, and Reptiles differ but little from those of modern times, and the Birds take on the diversity and relative importance which characterize them now. Above all, the Mammals undergo a wonderful expansion and take the place of the vanished reptiles, giving to Cenozoic time an altogether different character from all that went before it. The great geographical and climatic changes produced migrations of animals and plants upon a great scale, from continent to continent and from zone to zone, the result of which is the distribution of living beings over the earth's surface as we find it to-day.

There is some difference of usage regarding the subdivisions of the Cenozoic group, though the difference is principally with reference to the rank of those subdivisions. We shall follow the usual American practice of dividing the group into two systems, the *Tertiary* and *Quaternary*.

THE TERTIARY PERIOD

The names *Tertiary* and *Quaternary* are remnants of an old geological nomenclature which has lost its significance, and was proposed when the whole succession of strata was believed to be divisible into three groups, called the *Primary*, *Secondary*, and *Tertiary*, respectively. When it was learned that there were groups and systems much older than the so-called *Primary*, the name *Pa-*

læozoic was substituted for *Primary*, as was *Mesozoic* for *Secondary*, though the latter term is still used, especially in England. The name *Tertiary* has thus lost its meaning, but is nevertheless retained as a division of the Cenozoic group or era.

	Gulf Border	**Interior Region**	**Pacific Border**
PLIOCENE SERIES	Floridian Stage.	Blanco Stage. Goodnight Stage.	PLIOCENE (MERCED SERIES)
MIOCENE SERIES	Chesapeake Stage. Chipola Stage. Chattahoochee Stage.	Loup Fork Stage. { Nebraska Substage. Deep River Substage. John Day Stage.	MIOCENE (Auriferous gravels)
OLIGOCENE	?	White River Stage.	?
EOCENE SERIES	Upper: Vicksburg.	Uinta Stage.	TEJON SERIES
	Middle { Jackson. Claiborne. Lower Claiborne.	Bridger Stage. { Bridger Substage. Wind River Substage. (Green River)	
	Lower { Lignitic. Midway.	Wasatch Stage. Puerco. ? Fort Union.	

The great revolution which closed the Cretaceous and inaugurated the Tertiary has left its effects visible in all the continents, but the gap between the two periods is not everywhere the same. This revolution gave to North America nearly its present outlines, in consequence of which marine Tertiary beds occur only along the borders of the continent, while the Tertiary of the interior is all of fresh-water origin. In other continents, and especially in Europe, the distribution of land and sea was very different in the Tertiary from what it is now, and the topography of the land was profoundly altered in the course of the period. Some of the highest mountain ranges of the earth were upheaved in Tertiary times, such as the Atlas, the Alps, the Caucasus, and the Himalayas. That Tertiary ranges are high is not due to any extreme degree of compression as compared with that which produced older ranges, but merely to the youth of the former; denudation has not yet had time to sweep them away.

The Tertiary system or period is divisible into four quite well distinguished series or epochs, which may usually be identified in both the marine and fresh-water formations; but for lack of common fossils it is not yet possible to correlate the stages and substages of the interior region with those of the coast. In the preceding table, therefore, no exact comparison of these minor subdivisions is intended.

It has become customary to distinguish between the older and newer parts of the Tertiary by grouping together the Eocene and Oligocene into the *Palæogene*, and the Miocene and Pliocene into the *Neogene*. *Eocene* and *Neocene* are employed in the same way, but this is objectionable because it is using *Eocene* in two different senses.

The Eocene Epoch

The name *Eocene* is derived from two Greek words, — *eos*, dawn, and *kainos*, recent, — and was, like the names of most of the other Tertiary epochs, proposed by Lyell.

American. — Along the Atlantic and Gulf borders the coast-line of the Eocene closely follows that of the Cretaceous, of which only a narrow strip separates the Eocene from the Triassic and crystalline rocks of the Piedmont plain. The unconformity between the Cretaceous and Eocene indicates that along this coast the latter period had been inaugurated by an encroachment of the sea upon the land. The Mississippi embayment had nearly the same size and form as before, extending up to the mouth of the Ohio. Florida was entirely submerged, as was most of Central America, cutting off the northern from the southern continent. On the Atlantic coast the Eocene rocks are unconsolidated sands and clays, with some glauconitic greensand, particularly in New Jersey. They form a narrow belt through New Jersey, Maryland, and Virginia, widening into a quite broad band through the Carolinas and the Gulf States, and extending around the borders of the Mississippi embayment into Texas. In the Gulf region the rocks are more consolidated, and are quite hard limestones, sandstones, and shales, with extensive deposits of lignite, formed in ancient peat bogs which followed the low-lying Gulf shores.

On the Pacific coast a long, narrow arm of the sea occupied the great valley of California, extending northward into Oregon and Washington; its deposits are at present principally displayed along the eastern flank of the Coast Range. These deposits form a single series, the *Tejon*, which lies upon the Chico in apparent conformity; but the lowest Eocene is not represented in the Tejon, and in Oregon an unconformity between the two series has been detected.

It was in the interior region that the geographical changes wrought by the revolution at the end of the Cretaceous had the most marked effects. Even before that the movement of elevation had converted the interior sea into bodies of fresh and brackish water, in which the latest Cretaceous deposits, the Laramie and Livingstone, or Denver, had been laid down. The same conditions appear to have lasted into the Eocene over a part of the Great Plains country. Covering much of North Dakota and Montana and a wide area in Canada was a body of fresh water, in which were formed the *Fort Union* beds that overlie the Livingstone unconformably. From the evidence of the plants the Fort Union is believed to be the oldest Eocene, but this is still uncertain. Fresh-water beds with similar plants are found in Greenland and Alaska. At the end of Fort Union time the Great Plains, from Mexico to the Arctic Sea, were dried up; but then began the establishment of a series of fresh-water lakes in the region between the Wasatch and Rocky Mountain ranges. At present this is a region of high plateaus, elevated from 5000 to 7000 feet above the sea, but then it must have been much lower and can hardly have been enclosed by such high mountains as now encompass it. These lakes were not formed simultaneously, but successively, and together include the whole of Eocene time in an almost unbroken record.

The oldest of these lakes was the *Puerco*, a relatively small body of water, which covered the northwestern part of New Mexico and the southwestern part of Colorado. This was followed by the very much larger *Wasatch* lakes, of which there were several, nearly or quite contemporary. The principal body of water extended from New Mexico, over eastern Utah and western Colorado to the Uinta Mountains, around the eastern end of which it formed a strait, expanding again north of the mountains and covering all southwestern Wyoming to the Wind River Mountains. This great lake must have been 450 miles long by 250 miles wide in its broadest part. A second lake filled the Big Horn Basin of northwestern Wyoming, which, then as now, was shut in by mountains. In southern Colorado, east of the main range of the Rocky Mountains, were two small lakes believed to be of this age.

The *Bridger* lakes, which were much smaller than the Wasatch, were not all contemporaneous, but in part successive. The oldest one (*Wind River* substage) occupied the Wind River Basin, north of the mountains of that name. Two later lakes were in the upper Green River valley in Wyoming and a third in the same valley south of the Uinta Mountains. Finally, a small lake of this age occupied the *Huerfano Cañon* in southern Colorado.

A great mountain-making disturbance drained the Bridger lakes, elevating all the ranges to which the post-Cretaceous revolution had given birth and establishing a new lake basin, the *Uinta*. This basin lies principally to the south of the Uinta Mountains in northeastern Utah and northwestern Colorado, and occupies part of the basin of the Wasatch and Bridger lakes. The three stages of strata may be seen here, one over the other.

The rocks which were accumulated in these successive lake basins are principally sands and clays, with an occasional gravel bank. They are indurated but still soft rocks which weather readily and give rise to the characteristic bad-land scenery already described.

The Eocene epoch was brought to a close by a series of movements which added a narrow strip of land along the Atlantic and Gulf coasts, at the same time raising northern Florida into an island. In the interior the plateau region was elevated and drained, and no extensive bodies of water were ever established there again. Probably the upheavals at the end of the Bridger and at the end of the Eocene had made the climate much drier, by cutting off the moisture-laden winds.

Foreign.—The Old World Eocene has a very different development from that of North America, the eastern continents not assuming their present outlines till much later. At the close of the Cretaceous period extensive geographical changes had taken place in Europe, consisting chiefly in the retreat of the sea from wide areas which it had occupied in the Cretaceous. This was especially the case in Russia, northern Germany and France, and southern England, and in place of the great gulf which had occupied these regions (see p. 484) were found only scattered bodies of fresh and brackish water. At a later time the sea again advanced over part of these areas, which explains the general unconformity between the Cretaceous and Tertiary strata. In southern Europe the Mediterranean regained the great expansion which it had partly lost in the latter part of the Cretaceous, extending far over northern Africa, where there is a gradual transition between the Cretaceous and Eocene, and transgressing over southern Europe. A long, narrow arm of this sea extended from southern France, past the north side of the future Alps and Carpathians, into western Asia. Another narrow sea, or strait, extended down the east side of the Ural Mountains, from the Arctic Ocean to the expanded Mediterranean, completely cutting off Europe from Asia. From Asia Minor the Mediterranean extended across Persia and Turkistan, northern India, Borneo, and Java, to the Pacific, separating the southern peninsulas from the Asiatic mainland. There was thus a continuous sea around the earth, everywhere separating the southern continents from the northern.

In the Alpine and north African regions were accumulated thick masses of limestone, largely composed of the gigantic foraminiferal shells called *Nummulites*, but in northern Europe no such widely spread formations occur. After the Eocene had continued for some time, a marine basin, the Anglo-Gallic, was formed over southern England, northern France, and Belgium, which contains a succession of alternating marine, brackish, and fresh-water strata.

This basin is classic ground, for in it were made the studies of Cuvier and Brogniart, which led to the recognition of the Tertiary as a distinct system and founded the science of Palæontology.

On the west coast of Africa the sea encroached in a narrow belt. Australia has no marine Eocene, but New Zealand has extensive deposits of this epoch, between which and the Cretaceous no definite line can be drawn.

The Tertiary formations of South America cannot yet be correlated with those of other continents, and will be considered together in a separate section.

The Eocene thus had broad seas where now is land, and continents now connected were then separated by straits and sounds. On the other hand, there were then land bridges joining land areas which are now far apart. Some of these land bridges may be reconstructed with much confidence, while others are more or less probable. America was connected with Asia across what is now Bering's Sea, and also with Europe, probably by an extension of Greenland and Iceland. The Antarctic continent apparently had a much greater extension than it has now, and seems to have been joined with both Australia and South America. It is quite possible that Africa was more or less directly connected with the same land mass. If this be true, then in Eocene times the northern continents, Europe and Asia, were joined in the Arctic latitudes by way of North America, while South America, Africa, and Australia radiated in three great lines from the South Pole. Between the two series of continents, northern and southern, swept the transverse seas, of which the Mediterranean and Caribbean are remnants.

Eocene Life

Except for the Vertebrates, Eocene life is chiefly instructive from the manner of its distribution over the globe. Invertebrates and plants are nearly the same as modern forms, the genera, for the most part, still existing, though the species are nearly all extinct.

Plants. — The Eocene flora of North America is found preserved in widely separated localities, — Canada, Montana, Wyoming, and Idaho. It was very rich and varied, and bears evidence of a climate much milder than now obtains in those localities. Besides Ferns and Horsetails, this flora includes some Grasses, Bananas, and many noble Palms (Fig. 165), Myrtles, Beeches, Oaks, Willows, Poplars, Elms, Sycamores, Laurels, Magnolias, Maples, Walnuts, Pines, Spruces, Arbor Vitæ, and the like. Even in Greenland and Alaska was a luxuriant growth of forests of a temperate character, such as could not exist there now.

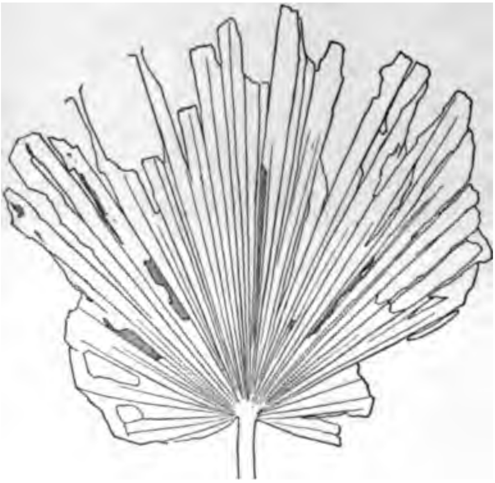

FIG. 165. — *Flabellaria eocenica*, 1/12. Green River Shales.

The European flora has a more decidedly tropical character than that of North America, and contains plants whose nearest living allies are now widely scattered, occurring in the warmer parts of America, Africa, Asia, and Australia. Cypresses, Yews, and Pines are abundant, including the *Sequoia*, now confined to California, and the *Gingko* of China and Japan. Aloes, Palms, and Screw-pines occur, mingled with the ordinary temperate forest trees, Elms, Poplars, Willows, Oaks, etc. The distribution of plants in the Eocene was thus very different from what it is at present.

Animals. — *Foraminifera* of relatively enormous size abounded, and their shells make up great rock masses. *Orbitolites* is a conspicuous genus along our Gulf coasts, *Nummulites* in the Old World. Corals are completely modern in character. The Sea-urchins and especially the *Irregulares* are much the most important representatives of the *Echinoderms*. Of the *Mollusca* both Bivalves

(Pl. XI, Figs. 2, 3) and Gastropods (XI, 4, 5) increase greatly and are very rich in species. Nautiloid Cephalopods are more varied and widely distributed than now (XI, 8), and in a few localities *Ammonites* and *Belemnites* have been found, but these are mere belated stragglers from the Cretaceous and are much too rare to be at all characteristic. Among the Crustacea should be noted the great increase of the *Crabs*, which are even more numerous and varied than in the Cretaceous.

The *Fishes*, both fresh-water and marine, differ only in minor details from modern fishes. The *Reptiles* are likewise essentially modern in character, and only two groups, the Lizards and Snakes, are more numerous than they had been in Mesozoic times, though the venomous snakes had not yet appeared. The Eocene lakes of the West contained multitudes of large Crocodiles and a great variety of Turtles.

Eocene *Birds* are very much more numerous, advanced, and diversified than those of the Cretaceous; one characteristic feature of the times was the presence in Europe and America of extremely large, flightless birds, more or less like the ostriches in appearance. Of flying birds there were many kinds; Owls, Eagles, Buzzards, Vultures, Gulls, Waders, Woodcock, Quail, Ibis, and Pelicans are represented by ancestral forms, somewhat different from their modern descendants.

The *Mammals* have developed in a marvellous way since the Cretaceous, assuming in terrestrial life that dominant place which they have ever since held. Compared with the evolution of other animal groups, that of the mammals has been so rapid that each stage of the Eocene has its own mammalian fauna, differing from those of the preceding and succeeding stages. Besides these geological differences between the successive mammalian assemblages, there are often marked geographical differences between the faunas which are of approximately contemporaneous age, but widely separated in space. Comparing Europe and North America in this respect, we find that in the Eocene each continent had its own peculiarities, but that the land connection between them allowed continual intermigration and thus kept up

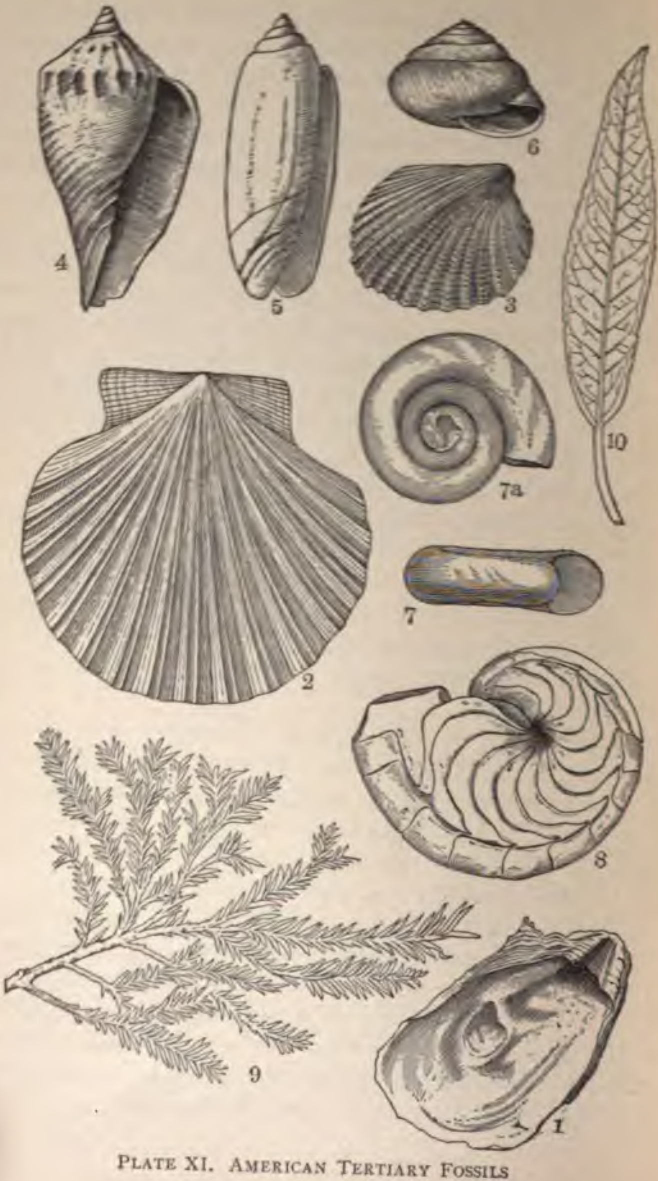

Plate XI. American Tertiary Fossils

a close general similarity in their mammals. The southern continents, on the other hand, had altogether different mammalian faunas, due to their long separation from the northern lands.

The PUERCO shows its close relations with the Mesozoic in the presence of numerous *Multituberculata*, the last and largest of that group. (*Ptilodus* and *Polymastodon* are the common genera.) The primitive type of flesh-eaters (*Creodonta*) and ancestors of the true Carnivores are abundant, as are also the primitive hoofed animals (*Condylarthra* and *Amblypoda*); the curious *Tillodonts*, *Ganodonts*, and primæval *Lemuroids* complete the list. Especially noteworthy is the entire absence of Rodents, of true Carnivores, of Artiodactyls, and Perissodactyls.

The change to the WASATCH is very abrupt, and was probably due to a great migration of mammals from some region, as yet unknown. *Rodents* come in for the first time in North America. *Perissodactyls* make their first appearance with ancestral members of the horse family (*Hyracotherium*), of the rhinoceroses (*Heptodon*), the tapirs (*Systemodon*), and other families now extinct. The curious extinct group of hoofed animals called the *Amblypoda* greatly increases in numbers and in stature, and both in Europe and America the predominant genus is *Coryphodon*. *Artiodactyls* also appear for the first time in ancestral members of the pigs (*Eohyus*), and the ruminants (*Trigonolestes*). The *Creodonts* increase in numbers and in the size and strength of the individuals, *Pachyæna* being as large as a bear, and *Oxyæna* was an aquatic form. Numerous *Lemuroids* and primitive types of *Monkeys* (*Anaptomorphus*) swarmed in the trees. The correspondence between the mammals of Europe and North America was never closer than in Wasatch times.

Between the Wasatch and Bridger lie the GREEN RIVER SHALES,

EXPLANATION OF PLATE XI, p. 504. 1. Ostrea virginiana, 1/2, Miocene. (Whitfield.) 2. Pecten madisonicus, 1/2, Miocene. (Whitfield.) 3. Cardita perantiqua, Eocene. (Whitfield.) 4. Volutolithes sayana, 3/4, Eocene. (Whitfield.) 5. Oliva carolinensis, 3/4, Miocene. (Whitfield.) 6. Helix Dalli, Miocene. (White.) 7. Planorbis convoluta, ? Fort Union. (Meek.) 8. Aturia Vanuxemi, 1/4, Eocene. (Whitfield.) 9. Glyptostrobus Ungeri, 1/2, Eocene. (Lesquereux.) 10. Salix sp., 3/4, Oligocene.

which are believed to represent the lower Bridger (*Wind River* substage) in time. These shales have yielded no mammalian remains, but great numbers of plants, insects, and fishes occur in them.

The BRIDGER mammals represent a steady advance upon those of the Wasatch, but there is no such complete change as followed the Puerco. The Perissodactyls may be said to culminate in the Bridger; for though they afterwards reached much higher stages of development, they never again had the same relative importance. Horses, Tapirs, Rhinoceroses, and Titanotheres (*Palæosyops*) are extraordinarily abundant. *Coryphodon* has vanished, but the wonderful elephantine, six-horned *Uintatherium* takes its place in North America, though not in Europe. Artiodactyls, Creodonts, Rodents, Tillodonts, and Lemurs were more diversified than ever, and Bats are found here for the first time.

In the UINTA the mammals continue to advance along the same lines, gaining in size and advancing in structure. Noteworthy is the appearance of the true Carnivores (*Cynodictis*), and the great development of the Artiodactyls, which in Europe display wonderfully manifold types of structure. In America Oreodonts (*Protoreodon*) and primitive Camels (*Leptotragulus*) are the commonest forms. Creodonts, Lemurs, and Tillodonts decline.

In the Upper Eocene seas great whale-like forms (*Zeuglodon*) of extraordinary appearance and structure had grown abundant.

Volcanic eruptions continued in the Rocky Mountain region during the Eocene. The Yellowstone Park was a centre of great activity, with numerous cones ejecting acid lavas and tuffs.

The *climate* of the Eocene was very much the same as in the Cretaceous, mild and equable all over the Northern Hemisphere, at least, as is shown by the character of the vegetation and the marine shells, though probably there was already a beginning of climatic zones.

THE OLIGOCENE EPOCH

American. — This term (derived from the Greek *oligos*, little, and *kainos*, recent) is seldom used in this country, but it is important to follow the European scale, wherever that is practicable. No marine beds are yet known in North America belonging to this series, but in the interior region are extensive fresh-water deposits which clearly should be referred to it, and which form the WHITE RIVER stage. The largest body of water of this time occupied northeastern Colorado, southeastern Wyoming, much of western Nebraska, and South Dakota. A second lake of unknown extent was in North Dakota, and may have been joined with the first; the present severance of the deposits may be due to the removal of the strata over the intervening territory. A third and much smaller area is in the Cypress Hills of the Canadian Northwest Territory. The strata formed in these waters, partly fluviatile and partly lacustrine deposits, are almost perfectly horizontal, and consist of pale-coloured, moderately indurated sands and clays, which weather into fantastic bad lands (see Figs. 23, 24, pp. 79, 80; Fig. 133, p. 317). In the South Park of Colorado, at Florissant, was a very small lake, probably of Oligocene date, in which showers of fine volcanic ashes formed thin, papery shales, which have preserved great numbers of plants and insects.

No very marked disturbance closed the White River age; the lakes were simply filled or drained and deposition ceased.

Foreign. — During the Eocene nearly all Germany had been land, but in the Oligocene it was invaded by the sea, which broke in from the north and covered all the northern plain, extending into Belgium, and sending long bays to the south. One of these reached to the strait on the north of the Alps, expanding into a large basin near Mayence and Frankfort. Over Germany the sea was shallow, permitting the formation of extensive peat bogs, where were accumulated masses of lignite or brown coal. In the basin of Paris the sea had a greater extent than in Eocene times, though with lacustrine beds intercalated, but in England the beds are more of brackish- and fresh-water origin. In southern Europe the sea retreated from wide areas, and in its place were extensive bodies of fresh and brackish water, in many of which peat bogs accumulated masses of lignite. Such lignitic deposits occur at intervals from the south of France, Switzerland, and

Bavaria, as far east as Hungary and Dalmatia. The Ural Sea was drained and Europe united with Asia.

Oligocene Life

Plants. — The shales of Florissant have yielded a very rich flora, which resembles that of the Eocene in general character, though with some marked differences. One such difference is the abundance of Conifers at Florissant, among them *Sequoia*, which have not been found in the American Eocene, and another is the great rarity of Palms. The flora is of a warm temperate, but not at all subtropical character. In Europe the Oligocene vegetation of the south is still subtropical, and contains an increasing number of plants like those which at present inhabit the warmer parts of North America. In northern Europe there is a change in the flora, palms being less common than they had been before.

Animals. — The *Insects* of Florissant are very numerous, and differ little from modern forms. They, like the plants and the *Fishes* of the same locality, resemble those now found in the warmer parts of the United States.

The White River beds contain a wonderfully rich and varied vertebrate fauna, and one which is very closely related to the contemporary fauna of Europe. The *Reptiles* show a great change from the Eocene; the large Crocodiles, which were so common, have vanished from the northern interior, and only one small and rare species has been found. The Turtles are still numerous, but not nearly so varied as in the Eocene.

Mammals have been preserved in astonishing numbers, and though they are much like those of the Uinta, they show great progress since that time. The true Carnivores now become abundant, represented by primitive Dogs, Sabre-tooth Cats, and Weasels, the latter family much more numerous in Europe, where also occur Civet-cats, a family that never reached America. The true Carnivores have displaced the Creodonts, which have all died out, except two curious genera, *Hyænodon* and *Pterodon*. The Lemurs and Monkeys (with one doubtful exception) have also disappeared from North America. Perissodactyls are still very abundant; the Horses are represented by the little three-toed *Mesohippus* (Fig. 166), the Tapirs by *Protapirus*, and the Rhinoceroses by many types, all of them hornless; thus *Metamynodon* was a heavy, aquatic animal, somewhat like a hippopotamus in appearance; *Cænopus* was a stout terrestrial form, and *Hyracodon* (Fig. 167) a long-legged, slender, running animal. The Titanotheres culminate in the huge *Titanotherium*, which had a pair of long horns on the nose. Artiodactyls are now much more numerous than the Perissodactyls, but are quite different in the two continents. Besides a number of curious extinct types common to the two regions, such as *Ancodus*, *Anthracotherium*, *Elotherium*, America has Oreodonts, Camels (*Poebrotherium*), Peccaries (*Perchœrus*), and the extraordinary little *Protoceras*, while Europe had a remarkable variety of Xiphodonts, Anoplotheres, true Swine, and true Ruminants. The Rodents of the White River stage are much more numerous and varied than before. Marmots, Squirrels, Beavers, Mice, Pocket-gophers, and Rabbits are already well established.

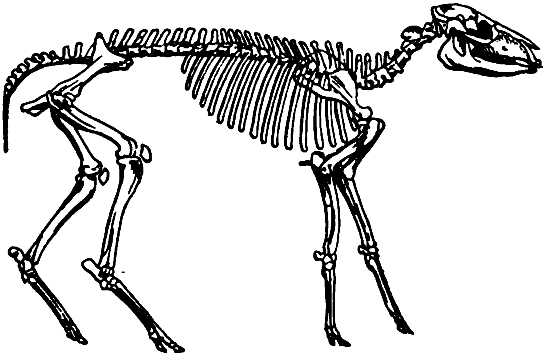

FIG. 166. — Skeleton of Mesohippus Bairdi. (Farr.)

From the change in the character of the vegetation and of the reptiles we may infer that a slight change had taken place in the climate, which was not quite so warm as before, at least in the interior of the continent. A similar change occurred in northern Europe in the later Oligocene.

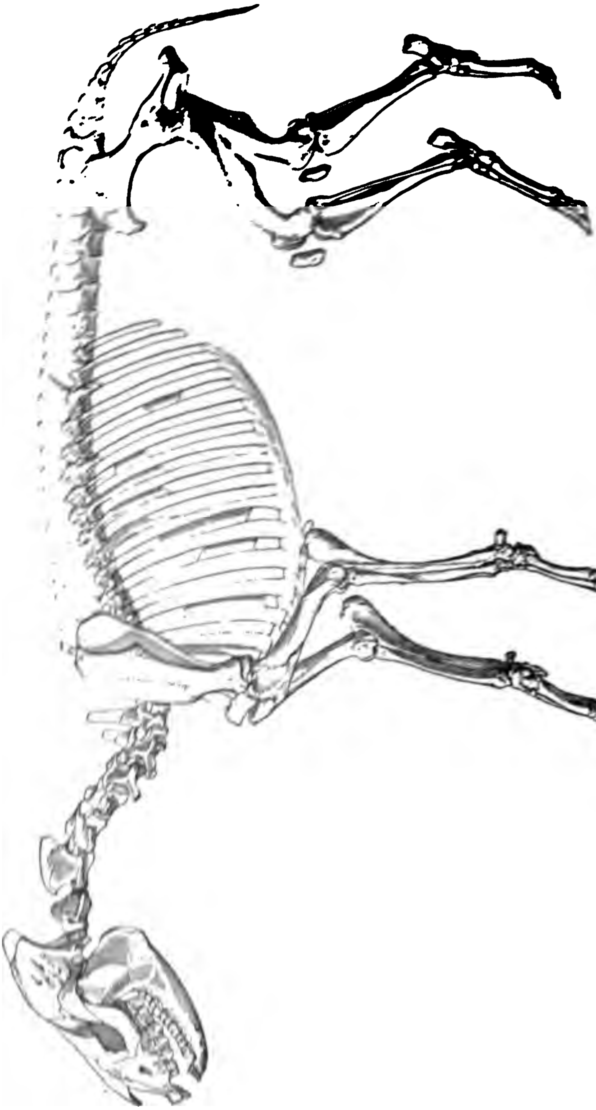

FIG. 167. — Skeleton of *Hyracodon nebrascensis*, 1/10.

THE MIOCENE EPOCH

American. — At the opening of the *Miocene*, the coast-line of the Atlantic and Gulf occupied nearly the same position as at the beginning of the Eocene, differing only by the presence of a narrow strip of coast and of the Florida island, which had been produced by the slight movements during or at the end of the Eocene. The whole thickness of the Miocene strata is not found everywhere along the coast; in Maryland and Virginia a slight transgression of the sea occurred, and Upper Miocene beds were deposited upon Lower Eocene. Miocene beds occur in Martha's Vineyard, are apparently concealed beneath the sea along the New England coast, and are continuous southward from New Jersey. In that state they have a thickness of 700 feet, thinning to 400 feet in Maryland, but attaining a thickness of 1500 feet in Texas. In the north the strata are unconsolidated clays and sands, but in Florida they are largely compacted limestones, and in Georgia, limestones and conglomerates. The Mississippi embayment was much narrowed by the Eocene uplift, and Miocene strata have not been found in Tennessee or Arkansas; in eastern Texas they are covered by newer deposits, but their presence is revealed by deep borings.

The older Miocene of the Atlantic and Gulf (*Chattahoochee* and *Chipola* stages) had a warm-water fauna very similar to that of the West Indies and Central America; some of the West Indian species ranged as far north as New Jersey. The newer Miocene, on the other hand (*Chesapeake* stage), shows a very marked faunal change which points to the influx of cooler waters. This change was probably due to the increasing size and elevation of the Florida island, and the formation of the "Carolina ridge" in the bed of the Atlantic, which diverted the Gulf Stream, pushing it farther away from the coast than it had been before, or than it is now. This allowed a cooler current from the north to follow the shore all the way down to the Gulf of Mexico. Central America was still, for the most part, under water, and rocks of Miocene age make up most of the interior mountain ranges of Costa Rica. Miocene strata, chiefly limestones, are also quite extensively developed in the West Indian islands.

In California an elevation at the end of the Eocene, or early in the Miocene, had shifted the shore-line far to the west. The late Cretaceous peneplain of the Sierra foothills had been elevated and carved into ridges. In the lower stream courses and the deepest parts of the valleys some heavy gravels had accumulated (the deep *Auriferous Gravels*). In the Upper Miocene the sea again advanced, raising the shore-line 420 feet above the present sea-level, depositing sediments (the *Ione* stage) along the foothills of the Sierra. In the stream valleys very thick masses of gravel were accumulated (the bench *Auriferous Gravels*). After the deposition of the gravels came a time of great volcanic activity in the Sierra, first, of rhyolite flows accompanied by sheets of tuff, and, after an interval, of andesite tuffs and breccias, which poured down the valleys as immense torrents of mud. Marine Miocene beds are found on both sides of the Coast Range, which then formed a chain of reefs and islands. Into the northern part of the Sacramento valley, the sea did not extend, this portion being occupied by a lake which is supposed to be Miocene. The coast of Washington and Oregon, including much of the Coast Range in the latter state, was covered by the sea, which extended up the valley of the Columbia and that of its southern tributary, the Willamette. Puget Sound was broader than now, and more widely connected with the Pacific; indeed, the whole peninsula between the sound and the ocean, with the Olympic Range, may have been submerged. The sea also extended over parts of the British Columbian coast. Alaska was depressed in the early Miocene, especially toward the north, and the valley of the Yukon was invaded by the ocean; probably the eastern part of Bering's Sea, and much of the lowlands of western Alaska, were covered with shallow water.

In the interior region are extensive fresh-water deposits of Miocene date. The oldest of these form the JOHN DAY stage of eastern Oregon, which spreads between the Cascade and Blue Mountains, and southward may extend into Nevada. The thickness of these beds is from 3000 to 4000 feet, and they are largely composed of stratified volcanic ashes and tuffs, which were showered into the lake by vents not very far away, probably in the Cascades. A second and much smaller lake of this age filled the central valley of Montana. The John Day age must have followed the White River after an interval which, geologically speaking, was quite short, and it seems arbitrary to refer the two stages to different epochs.

After the John Day lakes had been obliterated, no deposits were made in the interior region for a considerable period, and, so far as is yet known, the Middle Miocene is not represented in that region, but in the Upper Miocene these bodies of water were reëstablished on a greater scale than ever. The Loup Fork stage is composed of two substages, one of which is quite distinctly older than the other, and has a much more restricted range. This first substage, the *Deep River*, was formed in a lake, or several of them, which filled the mountain basins of central and southern Montana, north of the Yellowstone Park. The second substage, or *Nebraska*, is the most widely distributed of all the fresh-water Tertiary deposits of the interior, and is partly of lake, partly of river origin. The beds extend from South Dakota far into Mexico. Another area of these beds is in eastern Oregon, where they unconformably overlie the John Day. The Loup Fork is much thinner than the John Day and White River, and its rocks, sands, grits, and marls are scarcely at all indurated, not forming bad lands.

Besides these deposits whose geological position is established by the numerous fossils which they contain, there are several others which are referred to the Miocene, though with much doubt. One such lake occupied the upper Sacramento valley in California, and stretched far to the northeast through the narrow strait between the Sierra and the Coast Range; another was in western Nevada. Others again occupied valleys in the interior of British Columbia.

The Miocene was a time of great volcanic activity among the mountain ranges of the Pacific coast, and along the main range of the Rocky Mountains; the great volcanoes of Mexico and of the Cascade Mountains are believed to date from this epoch. The

Yellowstone Park continued to be an active volcanic centre, and was characterized by great ejections of basic andesites and basalts, both lavas and tuffs.

The close of the Miocene in North America was marked by some extensive geographical changes. Central America and the Isthmus were upheaved, joining North and South America, and cutting off the connection between the Atlantic and Pacific. The effects of this land bridge were soon made evident in the intermigrations of the land mammals which had been peculiar to one or other continent, South American types appearing in North America and *vice versa.* The same movement elevated the West Indian islands, and joined Florida to the mainland, adding at the same time a narrow belt to the Atlantic and Gulf coasts. Along the Pacific coast an upturning of the strata and elevation of the mountain ranges took place, though subsequent movements added much to the height of the mountains.

Foreign. — In the north of Europe the sea retreated from large areas; northern Germany was now dry land, with only a relatively small bay invading it, while England was entirely above water, and has no marine Miocene beds. On the west coast of Europe, the Atlantic encroached largely, as in France, Spain, Portugal, and also the northwest of Africa. Spain was joined to Africa, but straits across northern Spain and southern France connected the Atlantic with the Mediterranean. Another change of great importance was the shutting off of the long-standing connection of the Mediterranean with the Indian seas. The former covered much of eastern Spain, and flooded the lower Rhone valley, sending an arm along the northern border of the Alps to the neighbourhood of Vienna. Here it expanded into a broad basin, connected with another great basin covering Hungary. Most of Italy, Sicily, and a large part of northern Asia Minor were under water, but the Adriatic and Ægean Seas were mostly land, and the Alps formed a chain of islands, mountainous, but not nearly so high as at present.

At the end of the Lower Miocene came a great upheaval of the Alps, by which the sea was again excluded from that region, and, just as in the Oligocene, inland seas and lakes took the place of the marine straits. The basins of Vienna and Hungary had a very complex history, with repeated changes of size and position, resulting in the formation of an immense inland sea (the Sarmatian Sea), which reached from Vienna to the Black, Aral, and Ægean Seas, and was nearly as large as the present Mediterranean. This vast basin had but a limited connection with the ocean, and represented conditions much like those of the Black Sea at present. Europe had also a number of fresh-water lakes, particularly in France, Switzerland, and Germany, which have preserved a very interesting record of Miocene land life. A comparison with that of North America shows that a way of migration was still open between the two continents.

In the Old World the Miocene was a time of mountain making. The Pyrenees had been elevated in the later Eocene; the Alps received nearly their present altitude in the Miocene. The Apennines had two distinct phases of upheaval, one in the Eocene and one in the Miocene, the latter coinciding with that of the Alps. The Caucasus dates from the close of the Miocene, while the date of the Himalayas is yet uncertain, but was either Eocene or Miocene.

Marine Miocene beds occur in northeast Africa, on the coast of the Soudan, and in Australia and New Zealand.

Miocene Life

The life of the Miocene is in all respects a great advance upon that of the Eocene and Oligocene. The *Grasses* greatly multiply and take possession of the open spaces, producing a revolution in the conditions of food for the herbivorous animals. The vegetation of North America, as far north as Montana, perhaps even to northern British Columbia, still bore a southern character. In the Upper Miocene tuffs of the Yellowstone Park and contemporary strata of Oregon are found such trees as Poplars, Walnuts, Hickories, Oaks, Elms, Maples, Beeches, noble forms of Magnolias and Sycamores. One species of *Aralia* had leaves 2 feet long by 3 inches wide. Curiously enough, the Breadfruit (*Artocarpus*) flourished in Oregon, and probably on the Yellowstone also. Conifers were numerous and varied.

In Europe the lower Miocene flora was quite like that of modern India; over the central and western regions Palms continue to flourish, together with Live Oaks, Myrtles, Magnolias, Figs, etc. In the latter part of the epoch a change is noted, and such trees as Beeches, Poplars, Elms, Maples, Laurels, and the like become dominant.

Marine *Invertebrates* belong almost entirely to genera which still live in the seas, and many of the species persist to our own day. Both in North America and Europe the older Miocene has numbers of shells such as now live only in warm seas, like *Cypræa*, *Mitra*, *Murex*, *Strombus*, etc. (See Pl. XII.) The newer Miocene of our Atlantic coast was evidently a time of cooler waters, and a similar change took place in Europe.

The terrestrial *Vertebrates* of the interior are of much interest. Little is known of Miocene *Birds* in this country, but in Europe they are abundantly preserved and are of distinctly African character. Parrots, Indian Swallows, Secretary Birds, Adjutants, Cranes, Flamingoes, Ibises, Pelicans, Sand-grouse, and numerous Gallinaceous birds, were mingled with birds of European type, such as Eagles, Owls, Woodpeckers, Gulls, Ducks, etc.

The *Mammals* of the John Day are much like those of the White River Oligocene, but are more modernized and advanced. Ancient types, like the Creodonts, Anthracotheres, Titanotheres, aquatic and cursorial Rhinoceroses, have died out, while the Carnivores and Rodents greatly increase in numbers and variety. In Europe the Lower Miocene mammals are very similar to those of North America, but one marked difference is in the profusion of true Ruminants, of which the western continent had none.

Between the John Day and the Loup Fork is a long gap, as is also the case in Europe; consequently the change in the mammals seems very abrupt. The change consists partly in the extinction of old types, partly in the immigration of new forms, and partly in the development of the native stocks to more advanced grades. New arrivals are the *Mastodons*, a primitive type of elephant, and the true *Ruminants*. The earliest American forms of the latter (*Blastomeryx* and *Cosoryx*) have curious horns, somewhat like deer's antlers. A number of weasel- and otter-like Carnivores came in from the Old World, while the *Wolves*, *Panthers*, and *Sabre-tooth Tigers* were very numerous. Besides the true Ruminants, the American type of *Camels* and *Llamas* continued to flourish in such genera as *Procamelus*, *Pliauchenia*, and others. The Loup Fork Horses (*Protohippus* and *Hippotherium*) are much more modern in character and larger in size than their predecessors, but still have three toes on each foot. The Rhinoceroses are very abundant, and form a peculiar American genus (*Aphelops*) of massive, hornless animals. The Atlantic coast Miocene has yielded numbers of Dolphins, Sperm and Whalebone Whales.

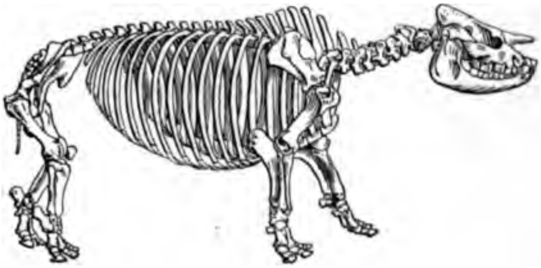

FIG. 168. — Skeleton of *Aphelops fossiger*. (Osborn.)

In Europe the Upper Miocene mammals were, in general, like those of North America, but a salient difference is in the much greater number of early types of Deer and Antelopes which are found there, together with various forms of Swine and ancestral Bears. Besides the Mastodons, which were common to both continents, Europe had in *Dinotherium* a remarkable kind of elephant; this animal had a much flattened head and a pair of massive, backwardly curved tusks in the lower jaw.

The *climate* of the early Miocene was much like that of the Oligocene and decidedly warmer in Europe than in North America, though it was mild even in the latter. The difference seems to have been largely due to the manner in which Europe was intersected by arms and gulfs of the warm southern sea. In the Upper Miocene the climate became somewhat cooler on both sides of the ocean.

THE PLIOCENE EPOCH

The term *Pliocene* is from the Greek *pleion*, more, and *kainos*, and refers to its close approximation to the present order of things.

American. — The Pliocene is not a conspicuous formation in this country, and only of late years has it been recognized at all on the Atlantic coast. The movements which closed the Miocene gave to the Atlantic and Gulf shores nearly their present outlines, but some differences may be noted. Much of southern Florida was still under water, and a gulf invaded northern Florida, covering a narrow strip of Georgia and South Carolina. Isolated patches of Pliocene rocks in North Carolina and Virginia may be remnants of a continuous band. A small part of eastern Mexico, much of Yucatan, and some of Central America were still submerged.

On the Pacific coast the post-Miocene upheaval had laid bare the western foot-hills of the Sierra and greatly disturbed the Miocene strata of the Coast Range. This range sank again early in the Pliocene, whose strata lie unconformably upon the Miocene, and extend over upon older beds. The transgression of the sea was limited, and Pliocene rocks form only a narrow band along the coast in California, Oregon, and Washington. The San Francisco peninsula was an area of subsidence and maximum deposition, for here no less than 5800 feet of sandstone (the *Merced* series) were formed, the thickest mass of Pliocene in North America. The mountains of British Columbia are believed to have been at a higher level than now, an elevation which probably connected Vancouver's and the Queen Charlotte Islands to the mainland. Marine Pliocene also occurs in southern Alaska.

In the interior are a number of Pliocene lake basins, the outlines of which have not yet been determined. The oldest of these formations is the *Goodnight* stage, named from a locality in Texas, where the beds lie unconformably upon the Nebraska substage of the Loup Fork. Similar beds have been found in northern Kansas and eastern Oregon, where they are closely connected with the Nebraska and followed them after no long interval. The second stage of fresh-water Pliocene is the *Blanco*, which extends over northwestern Texas into Oklahoma. Another small Pliocene lake occurred in southern Idaho, but its place in the series is not yet known.

The volcanic activity in the Rocky Mountain and Pacific coast regions, which had begun in the Cretaceous, continued through the Pliocene. The great outflow of rhyolite which built up the Yellowstone Park plateau is referred to the Pliocene. Near the end of the epoch, or perhaps after its close, occurred the enormous fissure eruptions, which flooded northern California and Nevada, southern Idaho, eastern Oregon and Washington, with thick sheets of basalt, obliterating the valleys and revolutionizing the system of drainage.

A problematical formation is the *Lafayette*, whose geological position and mode of origin are still debated. The Lafayette is a belt of sands and gravels which runs through Maryland, Virginia, the Carolinas, and the Gulf States, around the southern end of the Appalachians, up to southern Illinois, whence it turns southwestward to Texas. As in the typical exposures the Lafayette rests unconformably upon the Miocene and is unconformably overlaid by the Pleistocene, many authorities refer it to the Pliocene and regard it as a marine formation, while others believe it to be Pleistocene and to have been largely formed by waters derived from the melting of the first ice-sheet. The almost complete absence of fossils is a great obstacle to the settling of these questions.

At or near the close of the Pliocene, extensive upheavals took place in several different parts of the continent, especially on the Pacific slope. The rise of the Rocky Mountains continued, raising the western part of the Miocene lake beds 3000 feet higher than the eastern. The height of the Sierra was greatly increased by the rise of the mountains along the eastern fault plane and the tilting of the whole block westward. The new valleys cut through the late basalt sheets of the Sierras are much deeper than the older valleys excavated in Cretaceous and Tertiary times, which is due to the greater height of the mountains and consequent greater fall of the streams. The fault blocks which form the Basin Ranges were still further displaced, increasing their height.

The Wasatch Mountains and the High Plateaus of Utah and Arizona were again upraised. The great mountain range of the St. Elias Alps, in southeastern Alaska, was upheaved at this time, or even later, and the mountains of British Columbia were probably raised still higher. In Washington and Oregon the uplift was small, but became much greater in southern California, reaching 2500 feet in the Monte Diablo range. On the eastern side of the continent the uplift was on a much more restricted scale, not generally exceeding 100 feet. The Florida anticline underwent renewed compression, which increased its height; in Georgia, the continuation of this fold rose to 400 feet. The same movement extended the coast of Mexico and Central America and brought the continent to nearly its present outlines.

It is not necessary to suppose that all these movements were contemporaneous; merely that they occurred, now in one place, now in another, at or near the end of the Pliocene epoch.

Foreign. — In Europe the sea generally retreated at the end of the Miocene, leaving in the north only Belgium and a small part of northern France under water. In England the sea advanced upon the land; while in the Mediterranean region large areas remained under water, as in Spain, Algeria, nearly all of central and southern Italy and Sicily, and Greece. In this region volcanic activity was intense, and Ætna, Vesuvius, and the volcanoes of central Italy had begun their operations. Many bodies of fresh and brackish water existed over Europe, an older stage of the freshwater Pliocene occurring in southern France, near Athens, on the Island of Samos, and in Persia. Over the region of the great Sarmatian Sea of the Upper Miocene were numerous bodies of brackish water, in which lived shells much like those which now inhabit the Caspian. In India was a lake on the south side of the Himalayas, the deposits of which now make the Siwalik Hills, famous for their fossil bones; and similar deposits with the same fossils occur in Borneo.

Pliocene Life

The life of the Pliocene is very modern in character. Little is own of the vegetation in North America, but in Europe it is marked by the continued disappearance of the characteristically tropical plants and by an approximation to the modern European flora. Many trees persisted, however, which are no longer native to that continent, but are still found in eastern Asia or in North America, such as Tulip Trees, Magnolias, Sequoias, etc.

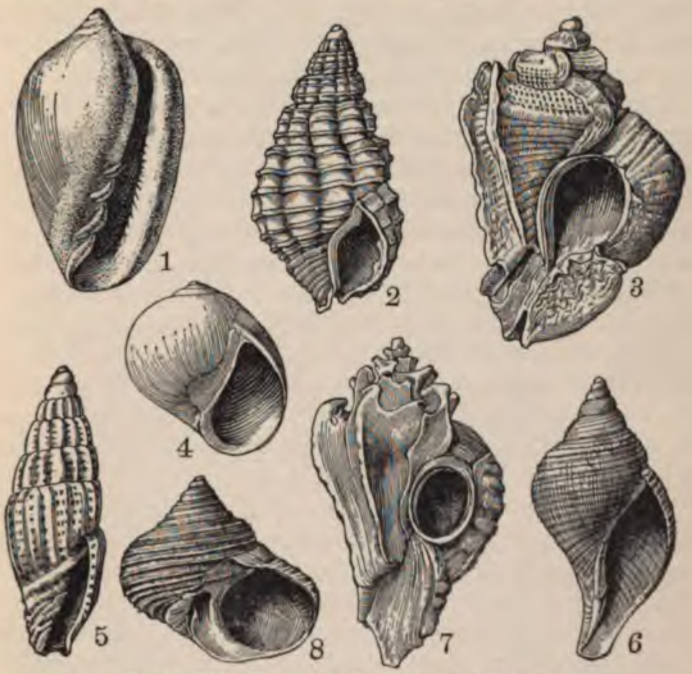

PLATE XII. TERTIARY FOSSILS FROM FLORIDA

1. Marginella aurora, 3/4, Miocene. 2. Nassa bidentata, 3/4, Miocene and Pliocene. 3. Murex Conradi, 2/3, Miocene. 4. Natica floridana, 1/2, Miocene. 5. Mitra Wilcoxi, 1/2, Miocene. 6. Fasciolaria tulipa, 1/2, Pliocene. 7. Typhis floridana, Pliocene. 8. Turbo rectogrammicus, 1/2, Pliocene. (After Dall.)

Marine *Invertebrates* are nearly identical with modern forms, and the great majority of Pliocene species of shells are still living.

The *Mammals* are still somewhat behind their modern successors, though much more advanced than their predecessors. Those of North America are still incompletely known, and the list is a short one. Mastodons, Horses, Rhinoceroses, Peccaries, and very large Llamas represent the hoofed animals. Besides the Dogs, Cats, and Mustelines, occur flesh-eaters, which are referred to the Hyænas. If the reference is correct, this is the only occurrence of these animals in America. The effects of the connection with South America are seen in the appearance of the gigantic Sloths and Armadillos, and of southern families of Rodents.

The early Pliocene mammals of southern Europe closely resemble those of modern Africa, — Wolves, Cats, Civets, Hyænas, Monkeys, Rhinoceroses, three-toed Horses, Deer (of which Africa has none), a great variety of Antelopes and of Giraffe-like forms, and Swine. Mastodon and Dinotheriun persisted, the latter attaining great size. India had a similar fauna, with certain geographical differences. Especially to be noted are the great variety of Oxen, the presence of Bears, true Elephants, and the Hippopotamus, of the first Old World Camels, and of the extraordinary *Sivatherium* and *Brahmatherium*, great, four-horned creatures allied to the Giraffes. In the Upper Pliocene the Elephants, Oxen, Hippopotamus, and Bears had extended their range to Europe, but not, so far as we know, to North America.

The *climate* of the Pliocene was evidently cooler than that of the Miocene, as is shown by the changes in the character of the vegetation and of the marine shells. The inference as to climatic change may be made with unusual confidence in this case, for nearly all the Pliocene *species* of shells are still living, and can hardly have changed their habits. In the English Pliocene the proportion of Arctic shells rises from 5% in the oldest to over 60% in the newest beds. The refrigeration was greater in the sea than on the land, for the vegetation shows that the air had not yet grown cold. That was to come later.

THE SOUTH AMERICAN TERTIARY

South America has comparatively little marine Tertiary. A narrow band of such strata is found on the Pacific coast, and some occur in Patagonia and Argentina. In these countries extensive and most richly fossiliferous fresh-water deposits are found interstratified with the marine. The succession, so far as known, is as follows: —

4. Araucanian Series, or Stage.
3. Santa-Cruzian Series, or Stage.
2. Patagonian Series, or Stage.
1. { Subpatagonian Stage.
   { Pyrotherium Beds.

The Subpatagonian and most of the Patagonian are marine, the others lacustrine. The mammals which are found more abundantly than in any other known deposits are, in all but the last of these formations, totally different from those of the northern continents. There are no Artiodactyls, Perissodactyls, Elephants, or Mastodons, neither Condylarthra nor Amblypoda; no Carnivores, Creodonts, Insectivores, or Bats. The very numerous genera of hoofed animals all belong to *orders* unknown in the north, — *Toxodontia* (Fig. 169), *Typotheria*, and *Litopterna*. There are Monkeys of South American type, and great numbers of Rodents, also South American, belonging exclusively to the Porcupine series (*Hystricomorpha*); no Squirrels, Marmots, Beavers, Mice, or Rabbits occur among them. A marvellous number of Edentates, Sloths, Armadillos, and Ant-eaters are found; and, most remarkable of all, numerous *Australian types of Marsupials*, both herbivorous and carnivorous, are a characteristic feature.

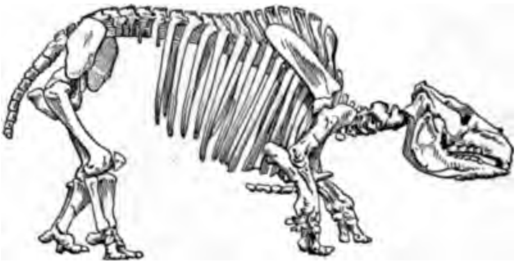

FIG. 169. — Skeleton of *Toxodon platense*. (Lydekker.)

Isolation from North America and some sort of a connection with Australia are clearly shown by these mammalian faunas. In the Araucanian formation the northern forms at last make their appearance. Wolves, Mastodons, Horses, Tapirs, Deer, Llamas, have found their way to South America, just as southern Sloths and Armadillos occur in the northern Pliocene.

From the absence of means for direct comparison, there has been much dispute concerning the true position of these South American formations in the Tertiary system. The only point so far at all well established is that the Araucanian beds cannot be older than the Pliocene, for we have much independent geological evidence to prove that the junction of North and South America was made by the post-Miocene movement.

CHAPTER XXXII

THE QUATERNARY PERIOD — (OR PLEISTOCENE)

In regions to which the great ice-sheets of the Glacial epoch did not extend the transition from the Tertiary to the Quaternary is perfectly gradual, so that it is often difficult or impossible to determine to which division a given set of strata should be referred. The seas at the end of the Pliocene had nearly the same extension as at present, and on the same coasts the same deposits continued to form. Even the Pliocene coral reefs continued uninterruptedly into the Pleistocene, so that any separation at all seems arbitrary. In the north, however, we find a very different state of things. In immense regions of North America, Europe, and Asia occur wide-spread evidences of vast glaciers and ice-sheets, in great masses of drift which cover the plains and choke the valleys, in successive lines of moraines, in great erratic blocks, sometimes weighing thousands of tons, which have been carried long distances from their parent ledges, and in the scored and polished rocks, the *rôches moutonnées* and other features which we have learned to be characteristic of ice action. The fossils also show the prevalence of a cold climate in these latitudes, and thus all the testimony agrees as to the great expansion of ice-sheets and glaciers in the early Quaternary.

THE GLACIAL OR PLEISTOCENE EPOCH

At the end of the Pliocene, it is believed that the North American continent was at a higher level than now, especially to the north, which favoured the accumulation of great masses of snow. It is still a matter of debate whether there was a single Glacial age or epoch, when the ice-sheet, once established, had many episodes of advance and retreat, yet never entirely disappeared, or whether there were several Glacial and Interglacial ages, when the ice alternately advanced and was completely melted away. There is much to be said on both sides of this question, but the present tendency among students of the Glacial epoch is to favour several distinct Glacial and Interglacial ages, one of the strongest arguments for which is the evidence given by the fossils of the return of mild and even warm climates. Professor James Geikie accepts no less than six Glacial and five Interglacial stages for Europe, and Professor Chamberlin finds evidence for five Glacial and four Interglacial stages in North America.

American.—At the times of great expansion the ice-sheets covered nearly all of North America down to latitude 40° N., anticipating the conditions of modern Greenland, though on a vastly larger scale. Three distinct centres or areas of maximum accumulation of the ice have been identified in northern Canada, from which the great ice-sheets flowed outward in all directions, though each one of the sheets had its own episodes of advance and retreat, so that the same region of country was overflowed, now by extensions from one sheet, and again by those from another. One of these centres of accumulation and distribution lay to the north of the St. Lawrence River, and on the highlands of Labrador, sending its ice-mantle southward over the Maritime Provinces, New England, and the Middle States, as far west as the Mississippi River. This is called the *Laurentide Ice-sheet* or *Glacier*. A second centre was near the west coast of Hudson Bay, and from this area the ice streamed outward in all directions westward toward the Rocky Mountains, northward to the Arctic Ocean, eastward into Hudson Bay, southward through Manitoba into the Dakotas, Minnesota, and Iowa. This great ice-sheet has been named the *Keewatin Glacier*, from the Canadian district of that name. A third centre was formed by the Cordillera of British Columbia, which for a distance of 1200 miles was buried under a great ice-mantle that flowed both to the northwestward and southeastward. The thickness of the ice in these vast flows was very great; over New England, the scorings on the mountain sides show that the ice was several thousand feet deep, only the highest peaks rising through it as nunataks.

In addition to the great ice-sheets which covered the northern parts of the continent, large local glaciers were developed in the Rocky Mountains, the Sierra Nevada, and other ranges of the western Cordillera. In these mountains almost every valley shows the evidences of former glaciation, both in its scored and polished sides and bed, and in the lines of moraine at its opening. Alaska, strange to say, was not glaciated, except locally, none of the great ice-sheets extending to it. Regarding the Great Plains region there is some difference of interpretation; by some authorities, especially Dr. G. M. Dawson, it is believed that the northern plains were covered with water and floating ice, while others suppose that the Keewatin and Cordilleran ice-sheets were joined, and buried all the country through northern Montana, Idaho, and Washington to the Pacific.

Deposits by the Ice-Sheets.—The general name for the materials deposited by the vast ice-sheets and the waters derived from them is *Drift*, which is both stratified and unstratified. The unstratified drift is that which is made by the action of the ice alone, and assumes several forms. (1) *Moraines*, lateral and terminal. These have already been described and need not detain us further. (2) *Till* is, when typically developed, a sheet of tough clay, which may be more or less sandy, crowded with stones and boulders of various sizes, and with no regularity of arrangement. Most of the stones and boulders show the evident marks of ice action, both in their form and in the scoring and polishing to which they have been subjected. The materials of till are principally derived from the bed rock upon which it rests, or from some spot close at hand, most of these materials having been transported only for short distances. A certain proportion of the stones, however, have been carried for long distances, as may be shown by tracing them to the ledges whence they were derived. Till is supposed to be the ground moraine of the ice-sheet, left behind and overridden when the descending ice reached more level ground, and packed into depressions. This explanation is, to some extent, conjectural, because the formation of similar deposits has not been observed in connection with modern glaciers; and several geologists do not accept the commonly received view of the origin of till, but regard it as the product of water and floating ice.

Stratified Drift is made by water, either alone or assisted by the action of ice. Much of the great mantle of Pleistocene drift is more or less completely stratified, because the border of the ice-sheets, whether they were advancing or retreating, was melting, and the drift left by the melting ice in its retreat was worked over more or less by water. Subglacial streams are active agents of deposition, both while still under the ice and after they have emerged. In long, winding tunnels beneath the ice they may leave the gravel ridges called *eskers*. Subglacial streams often are under great pressure and rise like fountains from beneath the ice-edge; the relief of pressure on escaping causes deposition at the edge of the ice-sheet. Drift thus piled in irregularities of the ice-front formed *kames*, which are billocks or short ridges of stratified drift, shaped by the recesses of the ice in which they gathered, and are often connected with the terminal moraines. Beyond the free border of the ice the escaping waters spread out stratified drift for considerable distances. When these waters descended valleys that were not too steep, they deposited sand and gravel in their descent, forming *valley trains*, which are of coarser materials and steeper grade near their heads than below. When the waters escaped from the ice away from valleys they spread out their deposits as *morainic* or *overwash plains*. The ice-front in several places entered the sea, and in others formed lakes by damming valleys and depressions; the ice-derived materials were, in such cases, rapidly deposited in quiet waters, as deltas and subaqueous overwash plains, and the finer silt and clay were carried further out into deeper water.

When the ice-cap was retreating, the processes described were continued along the shrinking border, until every part of the area once covered by the ice had been subjected to them, and thus the moraines left by the ice were covered with a more or less extensive and thick mantle of the stratified drift.

Along the border of an advancing ice-sheet, the same phenomena were repeated, but the kames, valley trains, lake deposits, etc., were incomplete because of the continually advancing ice, which overrode them, and, it may be, ploughed them up, or buried them under ground moraines, or otherwise modified them. The surface deposits of a glaciated region are those made by the ice and water during the final retreat.

Evidently, a succession of glacial episodes of alternately encroaching and shrinking ice-sheets must produce an exceedingly complex succession of stratified and unstratified drift, and it can cause little surprise that interpretations of such obscure phenomena should differ widely. If the successive deposits were separated by long, truly interglacial periods, then the sheets of drift must have been exposed to the denuding agencies for corresponding lengths of time, and will exhibit the various stages of chemical and mechanical disintegration appropriate to the length of exposure. There should be a manifest difference in this respect, between the earlier and the later deposits of drift.

For the reasons indicated, the chronological arrangement of the various parts of the drift, and the correlation of the deposits, glacial, lacustrine, and marine, of different regions of the continent are exceedingly difficult. The following classification has recently been proposed by Chamberlin for the drift of the Mississippi valley, but is only tentative and provisional.

Glacial or Pleistocene Series.

9. Wisconsin Till-sheets (earlier and later).
    8. Interglacial deposits (? Toronto).
7. Iowan Till-sheet.
    6. Interglacial deposits.
5. Illinois Till-sheet.
    4. Interglacial deposits (Buchanan).
3. Kansan Till-sheet.
    2. Interglacial deposits (Aftonian).
1. Albertan Drift-sheet.

The *Albertan* stage is typically displayed in the Canadian province of Alberta, where the first formation of drift was due to the extension of glaciers eastward from the Rocky Mountains. Farther east the till-sheet passes into the *Saskatchewan* gravels laid down by the waters derived from the ice-front. The materials of this drift are either local or came from the Rocky Mountains. The lowest drift deposits of the Mississippi valley are provisionally regarded as equivalents of the Albertan drift; they are best displayed in southern Iowa, but their extent has not yet been determined. According to some authorities the Lafayette formation should be correlated with the earliest glacial stage, rather than with the Pliocene.

A great retreat of the ice, if not its entire disappearance, brought about interglacial conditions at least in the Mississippi valley (*Aftonian* stage). The surface exposed by the retiring ice was rapidly occupied by vegetation, which in many places in Iowa, Minnesota, etc., formed accumulations of peat, sometimes to the depth of 25 feet. The *Kansan* stage represents the greatest extension southwestward of the ice-sheet, when the glacier descended from the north (perhaps the Keewatin glacier) nearly to the mouth of the Ohio River, and spread across Iowa and Missouri far into Kansas. Eastward, the sheet extended across the Mississippi River into Illinois. Again came a time of retreat, when the Kansan till was eroded, soil was formed, and peat deposited upon it (*Buchanan* stage). A renewed extension of the ice laid down the *Illinois* till-sheet, which is found not only in that state, but crossed into Iowa also. A fourth recrudescence of the glacier (*Iowan* stage) occasioned the deposit of another till-sheet, of an extent not yet determined, which is best displayed in northeastern Iowa, where it is intimately associated with the largest accumulations of loess in the Mississippi valley. The Iowan till-sheet is followed by interglacial deposits which are perhaps contemporaneous with those which are so well shown near Toronto on Lake Ontario. The latter beds form a succession of fine shales and sandstones that lie between two sheets of glacial drift, and contain fossil plants which indicate a milder climate than that of the present time at Toronto, near which these beds are found. Such a fact is difficult to explain, except as the result of truly interglacial conditions. The *Wisconsin* stage is much the most conspicuous and best known of all, and its sheets of till and drift are far thicker than those of the other Glacial stages. Especially conspicuous is the great terminal moraine which has been traced almost across the continent. Beginning at Nantucket, the moraine runs through Long Island and Staten Island to New Jersey, which it crosses into Pennsylvania; here it bends sharply to the northwest to the boundary of New York, but turns southwest almost at a right angle, reaching nearly to the Ohio River at Cincinnati. It crosses in an irregular, sinuous line the states of Indiana, Illinois, Iowa, and thence northwestward through the Dakotas and Montana into Canada, where it probably reaches the Arctic Sea.

In New England there is no clear evidence of more than one Glacial stage. In part, this may be due to the later development of the Laurentide glacier. The geologists of the Canadian Survey believe that, "beginning at the west and going eastward, these three great glaciers [*i.e.* the Cordilleran, Keewatin, and Laurentide] reached their widest extent and retired in succession." (Tyrrell.)

The final retreat of the ice was by slow stages with many halts. In the central West are preserved many lines of moraine, with kettle-holes, kames, and drumlins, which mark the successive pauses in the retreat.

An interesting episode of later Glacial times was the formation in Minnesota and Manitoba of a great body of fresh water, *Lake Agassiz,* which was 700 miles long from north to south.

The great Keewatin glacier, which had long occupied the basin of Lake Winnipeg and the Red River valley, began eventually to retreat northward, while the Laurentide glacier, which, it would seem, had begun to accumulate at a somewhat later date, gradually advanced to the westward. When the two sheets united, the withdrawal of the Keewatin glacier had left nearly or quite all of Manitoba free from ice. The junction of the Laurentide and Keewatin glaciers formed a continuous ice-wall on the north and east, shutting off the drainage, which seems before to have had a free course to Hudson Bay, and damming back the waters into a great lake. The lake rose until it overflowed southward into the Mississippi by means of the now extinct Warren River. As this river excavated its bed, it gradually lowered the water level of Lake Agassiz. The drainage of the lake seems to have been accomplished by the continued retreat of the Keewatin glacier until it became separated from the Laurentide sheet, leaving the way open around the northern edge of the latter to Hudson Bay.

In the non-glaciated parts of the continent occur stratified Pleistocene deposits, which it is very difficult to associate with the events taking place in the glaciated area, for lack of any means of direct comparison. On the Atlantic slope from New Jersey southward a succession of Pleistocene gravels and sands constitutes the *Columbian* formation, so called because of its typical development in the District of Columbia. These deposits are estuarine and marine deltas and shore sediments, partly submarine. Three phases of the Columbian have been recognized, the *fluvial*, *interfluvial*, and *low-level*. "The fluvial phase is found in its fullest development along the leading waterways. It consists of a lower horizon of coarse materials, pebbles, and boulders, generally passing upward into a brownish loam. The interfluvial phase is found typically represented in the country which lies between the waterways, and is characterized by materials of local origin and produced largely by wave action. The low-level phase is developed throughout the area farthest removed from the ancient shore-line. The deposits consist of sands, clays, and loams. They indicate a much less disturbed type of sedimentation than that found in either the fluvial or interfluvial phase. They were scattered as a coating of greater or less thickness over the eastern portion of the district, and have since suffered but little from denudation. The fossils are of recent species and indicate the marine origin of the deposits." (Clark.) At present these deposits are from 100 to 400 feet above sea-level and indicate a submergence and reëlevation of the middle Atlantic coast.

Over the Great Plains from South Dakota to Texas the surface formation is a fine, calcareous, sandy clay, which lies unconformably upon the eroded surfaces of older strata, from the Blanco to the Cretaceous. This formation may be called the *Sheridan* stage (*Equus Beds*), from Sheridan County, Nebraska, where it is admirably shown, and is Pleistocene in age, probably corresponding to one of the Glacial stages, though by some it is regarded as Pliocene.

In the Great Basin the Pleistocene was a time of far less arid climate than at present. In the eastern part of the Basin was established the great Lake Bonneville (see p. 146), which had an outlet to the north into the Snake River. The deposits of this lake show that it had two periods of expansion, separated by one of almost complete desiccation. Lake Lahontan, on the western side of the Great Basin, which had no outlet, had similar episodes of rise and fall. The two relatively moist periods when these lakes were high may correspond in time to the two stages of greatest advance of the ice-sheets, the Kansan and Wisconsin, but this is only conjectural.

In the Glacial epoch a subsidence had begun which continued until it became a very marked feature of the times. The depression was greatest toward the north and especially in the valley of the St. Lawrence; at the mouth of the Hudson, for example, the land stood about 70 feet below its present level, on the coast of Maine 150 to 300 feet, and in the St. Lawrence valley 500 to 600 feet below. The consequence of the depression was that an arm of the sea extended up the St. Lawrence nearly to Lake Ontario, which was little, if at all, above sea-level. Two long and narrow gulfs reached out from this sea, one up the valley of the Ottawa River and the other over Lake Champlain. The lines of raised beaches, the sands and gravels filled with marine shells, and the bones of whales and walruses, are the present evidences of this submergence (the *Champlain* stage). These beds, so named from their typical exposure of the shores of Lake Champlain, were formed probably after the St. Lawrence valley had been freed from the ice-sheet, but it is uncertain whether they were contemporaneous with, earlier, or later than the Columbian formation.

On the Pacific coast also we find evidences of submergence. The Chaix Hills in Alaska are made up of stratified moraine material 4000 to 5000 feet thick (see Fig. 61, p. 157), and at corresponding levels Champlain species of marine shells are found.

In California raised beaches occur as high as 1500 feet above the present sea-level, which were probably due to the same submergence, though they may be older. Pleistocene movements continued, it may be, into the Recent epoch, increased the height of the Sierra Nevada, Wasatch, and Basin Ranges, and of the high Plateaus of Utah and Arizona.

The late Pleistocene was a time of ameliorated climate and heavy rainfall, when the flooded rivers moved sluggishly, owing to the diminished slope, and spread sheets of sands, gravels, and clays over their flood plains and in their estuaries, through which they have subsequently cut terraces, when elevation had given them renewed power.

The events of the Glacial epoch, and the diastrophic movements which accompanied and followed it, have had the most important and wide-spread effects upon the topography of the glaciated regions. The sheets of drift, stratified and unstratified, have completely changed the surface of the country, and by filling up the pre-Glacial valleys, have revolutionized the drainage, only the largest streams being able to regain their old courses. Innumerable lakes, large and small, were formed in depressions, rock basins, and behind morainic dams, the contrast between the glaciated and non-glaciated regions in regard to the number of lakes in each being very striking. The events which led up to the formation of the great Laurentian lakes are connected with the successive phases of the Glacial epoch, but they are very complex and the phenomena are differently interpreted by different observers, so that only the briefest outline of them can be attempted in this place.

When the Laurentide glacier was retreating across the area now occupied by or tributary to the Great Lakes, its front acted as a great dam holding back the waters from descending the valley of the St. Lawrence, and forming ice-dammed lakes, whose form and size varied with the position of the ice-front. These lakes discharged their waters southward at various points where the divides were lowest. At one time, for example, when the eastern half of Lake Ontario was filled by the ice, a long lake extended along the ice-front from western New York to the site of Chicago, where was the outlet to the Mississippi. This body of water occupied parts of the basins of the present Lakes Ontario, Erie, Huron, and Michigan. When the continued retreat of the ice had freed the basin of Lake Ontario, the outlet is believed to have shifted to a low point near Rome (N.Y.)and to have discharged into the Mohawk River, a change which lowered the water-level by several hundred feet. The shallowed waters were no longer sufficient to cover the divides between the distinct lake basins, and three lakes were formed, — Lake Huron, still partly walled by ice, Lake Erie, and Lake Iroquois, which occupied the Ontario basin, but was larger and emptied into the Mohawk, for the St. Lawrence channel was still blocked by the ice-front.

None of these lakes had the size and position of their modern representatives. A gentle upheaval of the region, rising toward the northeast, shifted all the lakes to the southwest. Lake Huron, which had previously discharged its waters (it is believed by some authorities) by way of the Ottawa River, thus was given an outlet through the St. Clair River and became joined to Lake Erie, which thus received the overflow from the upper lakes. The complete removal of the ice, together with the diastrophic movements, gave to Lake Ontario its present size and shape and opened to it an outlet into the St. Lawrence.

The Pleistocene was closed and the Recent epoch inaugurated by a movement of upheaval which raised the continent to its present height.

FOREIGN PLEISTOCENE

The Glacial epoch in Europe ran a course remarkably parallel with its history in North America. After the first Glacial and Interglacial stages (perhaps representing the Albertan and Aftonian), came the time of the greatest expansion of the ice, the *Saxonian* stage of Geikie, which is believed to correspond to the Kansan of America. The great centre of dispersion was the Scandinavian peninsula, where the ice was probably 6000 to 7000 feet thick, and whence it flowed outward, filling the Baltic and North

Seas, and covering Finland, northwestern Russia, the lowlands of Germany, and extending to England. The Highlands of Scotland were a secondary centre, its ice-sheets flowing into the North Sea and uniting with those from Scandinavia, and westward to the ocean. The Irish Channel was also filled up. From the southwest of Ireland to the North Cape of Norway, a distance of 2000 miles, was probably a continuous wall of ice fronting the sea, like that which now surrounds the Antarctic continent. At the same time the Alps were the seat of enormous glaciers, only the highest peaks rising above the sheets of ice, and these great glaciers extended far out from the foot of the mountains, covering all the lowlands of Switzerland and extending from Austria and Bavaria, on the east, to the Rhone valley near Lyons, on the west. The high plateau of Asia, from the Himalayas to Bering's Sea, shows evidences of glaciation, and great valley glaciers were formed on the southern slopes of the Himalayas, extending in some places to within 2000 feet of the sea-level.

A second great Glacial stage (the fourth Glacial or *Mecklenburgian* of James Geikie) is generally recognized in Europe and correlated with the Wisconsin stage of America. This ice-sheet was much less extensive than the former one, being confined principally to Finland, Scandinavia, the Baltic Sea, which it filled, Denmark, and a little of north Germany. The prevailing motion of this sheet was from east to west. The Alpine glaciers were also extended far beyond their present limits, but not so widely as before.

Following the Mecklenburgian stage came alternating periods of milder and colder climates, the fourth and fifth Interglacial, and fifth and sixth Glacial stages of Geikie, the Glacial stages marked, not by the formation of great continental ice-sheets, but by the extension or recrudescence of local snow-fields and valley glaciers. Oscillations of level also occurred along the coasts, allowing limited transgressions of the sea.

No evidence of continental ice-sheets has been found in the Southern Hemisphere, but high mountains like the Andes, the New Zealand Alps, and the Australian Alps had very large glaciers, probably contemporaneous with those of the Northern Hemisphere, and Patagonia was extensively glaciated.

The causes of the climatic changes which led up to the Glacial epoch and to the later disappearance of the ice-sheets, are still wrapped in mystery. Many attempts have been made to solve this most difficult problem, but none is convincing or satisfactory.

Pleistocene Life

The frequent and extreme climatic changes, of which we find such abundant evidence in the Pleistocene, caused extensive migrations and dispersions of animals and plants, and the rapid succession of Arctic and temperate forms. Many land bridges between different continents, or between continents and what are now islands, were not severed until the end of the Pleistocene, permitting migrations which are no longer possible. The extension of the ice-sheets brought with them Arctic floras and faunas, which retreated in the Interglacial times, while temperate animals and plants spread northward to replace them. These conditions produced a very severe struggle for existence and were fatal to a great many large mammals, causing numerous extinctions over the larger part of the world.

Pleistocene *plants* are almost all of the same species as those now living, but they are often very differently distributed. The Glacial cold greatly impoverished the European forests, which in the Pliocene had many kinds of trees now found only in North America or in eastern Asia. Owing to the east and west trend of the European mountains, the forests could not retire before the ice, and return, as they did in the United States, where no mountain barriers shut them off from the warm latitudes of the south. When the ice-sheets melted and the climate was ameliorated, the Arctic flora and fauna were forced to retreat in their turn; they did so not only by following the retiring ice-front, but also by ascending the mountains as the latter were cleared of ice. Thus, high mountains in the Northern Hemisphere have on their upper slopes an Arctic flora and fauna, separated, perhaps, by hundreds of miles from the nearest similar colony. For example, the higher parts of the White Mountains have plants which do not occur on the lowlands until Labrador is reached, and the snowy Alps have truly Arctic plants and animals.

Of Pleistocene *animals* it is only the mammals that require mention. Here also we find the same mingling of northern and southern forms, and association of types now widely separated. North America had Mastodons, Elephants, Horses, Tapirs, the first Bisons (which had migrated from the Old World, as had several kinds of Deer and the Musk-ox), Peccaries and huge Llamas, Wolves, great Cats as large as lions, Sabre-tooth Tigers, and the first Bears, also immigrants. A great variety of Rodents is found, most of them kinds which still inhabit the country, but mingled with these are South American forms like the Cavies and Water Hog (*Hydrochœrus*), and the giant Beaver (*Castoroides*) is an altogether peculiar form. Enormous Sloths (*Megatherium*, *Mylodon*, and *Megalonyx*) and Armadillos (*Glyptodon*) show that the way of migration from the south was still open.

In South America were an astonishing number of huge Edentates: Sloths nearly as large as elephants, Ant-eaters, and a marvellous variety of giant Armadillos. Some of the immigrants from the north, which are now extinct, still lingered in the Pleistocene, such as the Mastodons and Horses.

Europe was the meeting-ground of mammalian types now widely scattered. Together with Arctic forms like the Reindeer, Musk-ox, Mammoth (Hairy Elephant), Hairy Rhinoceros, and the Lemming (*Myodes*) were found southern animals, such as the Hippopotamus, several kinds of Elephants and Rhinoceroses, Lions, and Hyænas, and likewise species allied to those still living in Europe, such as the huge Cave Bear, the gigantic Irish Deer (*Megaceros*), and great Oxen. Northern Africa was joined to Europe by way of Malta and Sicily, and probably at Gibraltar also, permitting frequent intermigrations. The junction of Ireland with Great Britain and of both with the continent continued until after the ice-sheets had disappeared, so that these islands, and especially Great Britain, were stocked by the continental animals and plants.

In the Pleistocene of India are found many animals which now live only in Africa, such as the Baboon, Spotted Hyæna, etc.

Australia had a Pleistocene mammalian fauna composed, with the exception of the Wild Dog (*Canis dingo*), of Marsupials, allied to those which still inhabit that region, but many of them were of vastly greater size than the living forms.

The Pleistocene mammals are remarkable for the great size which distinguishes many of them, and it is just these which have passed away, leaving a world that is "zoölogically impoverished," but is nevertheless a much more agreeable place of residence without them. Further we note, (1) that the Pleistocene mammals are in general like the smaller forms which have succeeded them in the same regions, but (2) that in Europe and North America there was a commingling of types now found only in widely separated regions.

Man first appears in Europe in Glacial times; there is no known reason why he should not have existed in North America at the same time, but as yet convincing proof of his presence here has not been obtained. In the Recent epoch his works of art become numerous, but here the science of Anthropology begins.

We have now taken a very brief and hurried survey of the earth's history from its beginning as a nebula to the condition in which we find it to-day. The story of millions of years has been compressed into a few pages, and in this compression it is impossible that the history should not have suffered some distortion. Events widely separated in time and space are brought close together, just as two stars that are really separated by well-nigh infinite distances may seem to touch. Yet even from an imperfect outline sketch certain great truths may be learned. We see that the whole development of the earth has been under the domain of law, that events do not happen capriciously or by chance, but in an orderly, definite way, and for good and sufficient reasons. True, the earth is but a very small member of the Solar System, and the latter an inconsiderable member of the Universe, so that we might be tempted to think of the earth as such a mere speck that its history cannot be of much significance. But this would be to confuse greatness with mere bigness, to exalt Siberia above Greece in the development of mankind. It is as the manifestation and theatre of intelligence, of conscious life, that the earth possesses importance and real significance, however tiny it may appear when compared with the inconceivable vastness of the Universe. The obvious lesson of the whole history is that of progress and development, not only of the globe itself, but of the living things upon it, the lower giving way to the higher, the simple to the complex. Last of all appears Man, "the heir of all the ages," himself the crowning work of progress, who alone of living beings has been able in large measure to emancipate himself from the tyranny of natural forces. But if this emancipation is to justify itself and prove no mere mockery, it must result not simply in material improvements, but in advancement and progress along all lines that shall lift the race to a higher plane and make it worthy of its opportunities and of the age-long preparation for its coming.

"The solid earth whereon we tread

"In tracts of fluent heat began
And grew to seeming-random forms,
The seeming prey of cyclic storms,
Till at the last arose the man;

"Who throve and branch'd from clime to clime,
The herald of a higher race,
And of himself in higher place,
If so he type this work of time.

* * * * * *

"——— Arise and fly
The reeling Faun, the sensual feast;
Move upward, working out the beast,
And let the ape and tiger die."

APPENDIX I

In order to avoid the necessity of correlating the American and foreign geological subdivisions, comparatively few names of the latter have been mentioned in the text, because such correlations, in the present state of knowledge, can seldom be made with confidence. Subjoined are tables of the more important European formations.

CAMBRIAN SYSTEM

ENGLAND		SCANDINAVIA
Upper Cambrian, *Olenus* or *Dicellocephalus* Beds.	Lingula Flags.	*Olenus* Shales.
Middle Cambrian or *Paradoxides* Beds.	Menevian and Solva.	*Paradoxides* Beds.
Lower Cambrian or *Olenellus* Beds.	Caerfai.	Fucoid and *Eophyton* Sandstone.

ORDOVICIAN SYSTEM

ENGLAND	SCANDINAVIA
Bala.	Brachiopod Shales. *Trinucleus* Shales.
Llandeilo.	*Chasmops* and Cystidean Limestones.
Llanvirn. Arenig.	*Orthoceras* Limestone.
Tremadoc.	*Ceratopyge* Limestone.

SILURIAN SYSTEM

ENGLAND	SCANDINAVIA
Ludlow. Wenlock. Llandovery.	Gotland Limestone.

DEVONIAN SYSTEM

	ENGLAND	SCOTLAND	GERMANY
Upper Devonian	*Cypridina* Slates. *Goniatite* Limestones and Shales. Massive Limestones.	Old Red Sandstone.	*Clymenia* Limestones and *Cypridina* Slates. *Goniatite* Limestones.
Middle Devonian	Middle Devonian Limestones. Ashpringian Volcanics. Eifelian Slates and Limestones.		*Stringocephalus* Beds. *Calceola* Beds.
Lower Devonian	Grits and Sandstones.		Coblenz Beds. Hunsrück Slates. Sericitic Phyllite.

CARBONIFEROUS SYSTEM

	ENGLAND	GERMANY
Coal Measures	Upper (Ardwick) Series. Middle Series. Lower (Ganister) Series. Millstone Grit.	Ottweiler Beds. Saarbrück Beds.
Lower Carboniferous	Yoredale Series. Scar or Mountain Limestone. Lower Limestone Shales.	Culm.

PERMIAN SYSTEM

GERMANY

Zechstein.
Rothliegendes.

TRIASSIC SYSTEM

GERMANY	MEDITERRANEAN REGION	
Rhætic.	Bajuvaric Series	Rhætic Stage. Juvavian Stage.
Keuper.	Tirolic Series	Carinthian Stage. Norian Stage.
Muschelkalk.	Dinaric Series	Upper Muschelkalk. Lower Muschelkalk.
Bunter Sandstone.	Scythic Series	Werfen Beds.

JURASSIC SYSTEM

ENGLAND			GERMANY
Oölite	Upper	Portland.	Malm.
		Kimmeridge Clay.	
	Middle	Coral Rag.	
		Oxford Clay.	
		Kellaways Rock.	
	Lower	Great Oölite.	Dogger.
		Inferior Oölite.	
		Lias.	Lias.

CRETACEOUS SYSTEM

ENGLAND			FRANCE
			Danian.
Upper Cretaceous	Chalk	Upper.	Senonian.
		Middle.	Turonian.
		Lower.	Cenomanian.
	Upper Greensand.		
Lower Cretaceous	Gault.		Albian.
	Lower Greensand.		Aptian.
	Wealden and Purbeck.		Neocomian.

TERTIARY SYSTEM

Pliocene

ENGLAND	ITALY	FRESH WATER
Chillesford Beds.	Arno Stage.	
Norwich Crag.	Piacentine Stage.	
Red Crag.	Zancleano Stage.	
Coralline Crag.		Pikermi, Attica.
		Mt. Lébéron, France.

Miocene

FRANCE		VIENNA BASIN
Marine	*Fresh Water*	
Pontian.	Sansan.	Pontian Stage.
Sarmatian.		Sarmatian Stage.
Tortonian.	St. Gérand le Puy.	Second Mediterranean Stage.
Langhian		First Mediterranean Stage.

Oligocene

	PARIS BASIN	NORTH GERMANY
Tongrian	Fresh-water Limestone of Beauce and Upper part of Fontainebleau Sandstone.	Sternberg Rock. Sands of Cassel.
	Fontainebleau Sandstone.	Septaria Clay and Stettin Sand.
Ludian.	Gypsum of Montmarte.	Egeln-Latdorf Clays.

Eocene

PARIS BASIN	LONDON BASIN
Sand of Beauchamp and Limestone of St. Ouen.	Lower Headon Beds. Barton Clay.
Calcaire grossier. Sand of Cuise.	Bagshot and Bracklesham Beds.
Clay and Lignite of Soissons.	Woolwich and Reading Beds.
Sand of Bracheux. Marl of Meudon.	Thanet Sand.

APPENDIX II

For convenience of reference, the system of classification of the animals and plants which has been used in the book is here given in tabular form, omitting those groups which possess no importance as fossils. Groups marked with an asterisk (*) are extinct.

ANIMALS

A. PROTOZOA

- RHIZOPODA
  - **Foraminifera**
  - **Radiolaria**

B. METAZOA

- I. SPONGIDA, Sponges
- II. CŒLENTERATA
  - Class 1. **Hydrozoa**
    - *a. Hydroidea*, *b. Siphonophora*, *c. Discophora*, Jelly-fishes
  - Class 2. **Anthozoa**
    - *a. Alcyonaria*, *b. Zoantharia*, Corals
      - α. Tetracoralla
      - β. Hexacoralla
  - Class 3. **Ctenophora**
- III. VERMES, Worms
- IV. ECHINODERMATA
  - Class *1. **Cystidea**
  - Class *2. **Blastoidea**
  - Class 3. **Crinoidea**, Crinoids
    - **a*. *Palæocrinoidea* (Tessellata), *b. Neocrinoidea* (Articulata)
  - Class 4. **Asteroidea**
    - *a. Ophiurida*, Brittle-stars, *b. Stellerida*, Star-fishes
  - Class 5. **Echinoidea**, Sea-urchins
    - Subclass *A*. *PALÆOECHINOIDEA
    - Subclass *B*. EUECHINOIDEA
      - Order *a. Regulares*, Regular Sea-urchins
      - Order *b. Irregulares*, Spatangoids, Sand-dollars
  - Class 6. **Holothuroidea**, Sea-cucumbers

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- V. ARTHROPODA
  - Class 1. **Crustacea**
    - Subclass *A*. *TRILOBITA
    - Subclass *B*. GIGANTOSTRACA
      - *a*. **Eurypterida* (Merostomata)
      - *b*. *Xiphosura* (Limuloidea), Horseshoe-crabs
    - Subclass *C*. ENTOMOSTRACA
      - *a*. *Ostracoda*, *b*. *Phyllopoda*, *c*. *Copepoda*, *d*. *Cirripedia*, Barnacles
    - Subclass *D*. MALACOSTRACA
      - Order *a*. *Euphausiacea*
      - Order *b*. *Mysidacea*
      - Order *c*. *Decapoda*
        - Suborder *α*. *Macrura*, Lobsters, etc.
        - Suborder *β*. *Anomura*, Hermit-crabs, etc.
        - Suborder *γ*. *Brachyura*, Crabs
      - Order *d*. *Cumacea*
      - Order *e*. *Isopoda*
      - Order *f*. *Amphipoda*
      - Order *g*. *Stomatopoda*
  - Class 2. **Arachnoidea**, Spiders and Scorpions
  - Class 3. **Myriapoda**, Centipedes
  - Class 4. **Insecta**, Insects
    - Order *a*. *Orthoptera*, Cockroaches, Grasshoppers, etc.
    - Order *b*. *Neuroptera*, Caddis-flies, Ant-lions, etc.
    - Order *c*. *Hemiptera*, Cicadas, etc.
    - Order *d*. *Diptera*, Flies
    - Order *e*. *Lepidoptera*, Butterflies and Moths
    - Order *f*. *Coleoptera*, Beetles
    - Order *g*. *Hymenoptera*, Bees, Wasps, Ants, etc.
- VI. BRYOZOA, Sea-mosses
- VII. BRACHIOPODA, Lamp-shells
  - Order *a*. *Articulata*
  - Order *b*. *Inarticulata*
- VIII. MOLLUSCA
  - Class 1. **Pelecypoda**, Bivalves
    - Order *a*. *Asiphonida*, Oysters, Mussels, etc.
    - Order *b*. *Siphonida*, Clams, etc.
  - Class 2. **Glossophora**
    - Subclass *A*. SCAPHOPODA, Tusk-shells
    - Subclass *B*. PLACOPHORA, Chitons

Subclass *C.* GASTROPODA, Univalves
Order *a. Prosobranchia*, Conches, Whelks, Cowries, etc.
Order *b. Heteropoda*
Order *c. Opisthobranchia*, Sea-slugs, etc.
Order *d. Pulmonata*, Snails, etc.
Subclass *D.* PTEROPODA, Pteropods
Class 3. **Cephalopoda**
Order *a. Tetrabranchiata*
Suborder α. *Nautiloidea*, Nautilus, etc.
Suborder β. **Ammonoidea*, Ammonites
Order *b. Dibranchiata*
Suborder α. *Decapoda*, Cuttle-fishes, etc.
Suborder β. *Octopoda*, Octopus, etc.

IX. VERTEBRATA
Class 1. **Cyclostomata**, Lampreys
? **Ostracodermata*
Class 2. **Pisces**, Fishes
Subclass *A.* SELACHII, Sharks and Rays
Subclass *B.* HOLOCEPHALI, Chimæroids or Spook-fishes
Subclass *C.* DIPNOI, Lung-fishes
Order *a. Sirenoidei*, Existing Lung-fishes
Order *b.* ?* *Arthrodira*
Subclass *D.* TELEOSTOMI
Order *a. Crossopterygii*
Order *b. Actinopterygii*
Suborder α. *Chondrostei* or *Ganoids*, Sturgeon, Gar-pike, etc.
Suborder β. *Teleocephali* or *Teleosts*, Herring, Salmon, etc.
Class 3. **Amphibia**
Order *a.* **Stegocephala*
Order *b. Gymnophiona*, Snake-like Amphibians
Order *c. Urodela*, Mud-puppies, Salamanders
Order *d. Anura*, Frogs and Toads
Class 4. **Reptilia**, Reptiles
Order *a.* **Proganosauria*
Order *b. Rhynchocephalia*
Order *c.* **Ichthyosauria*
Order *d.* **Plesiosauria*
Order *e. Testudinata*, Turtles and Tortoises
Order *f.* **Theromorpha*
Order *g. Lepidosauria*

Suborder α. _Lacertilia_, Lizards
Suborder β. *_Pythonomorpha_
Suborder γ. _Ophidia_, Snakes
Order *h*. _Crocodilia_, Crocodiles
Order *i*. *_Dinosauria_
Order *k*. *_Pterosauria_
Class 5. **Aves**, Birds
Order *a*. *_Saururæ_ (Archæopteryx)
Order *b*. _Ratitæ_, Wingless Birds, Ostriches, etc.
Order *c*. _Carinatæ_, Flying Birds, Eagles, Sparrows, Doves, etc.
Class 6. **Mammalia**, Mammals
Subclass *A*. PROTOTHERIA
Order *a*. _Monotremata_, Spiny Ant-eater, Duck-billed Mole
Order *b*. ? *_Multituberculata_
Subclass *B*. METATHERIA
Order *a*. _Marsupialia_, Opossums, Kangaroos, etc.
Subclass *C*. EUTHERIA, Placentals
Order *a*. _Edentata_, Sloths, Armadillos, Ant-eaters
Order *b*. _Cetacea_, Whales, Dolphins
Order *c*. _Sirenia_, Sea-cows, etc.
Order *d*. _Insectivora_, Moles, Shrews, Hedgehogs, etc.
Order *e*. _Cheiroptera_, Bats
Order *f*. *_Creodonta_
Order *g*. _Carnivora_, Dogs, Cats, Weasels, Bears, Seals, etc.
Order *h*. *_Tillodonta_
Order *i*. _Rodentia_, Squirrels, Beavers, Mice, Porcupines, Rabbits, etc.
Order *j*. *_Condylarthra_
Order *k*. *_Amblypoda_
Order *l*. *_Typotheria_
Order *m*. *_Litopterna_
Order *n*. *_Toxodontia_
Order *o*. _Proboscidea_, Elephants
Order *p*. _Artiodactyla_, Swine, Camels, Deer, Oxen, etc.
Order *q*. _Perissodactyla_, Horses, Tapirs, Rhinoceroses
Order *r*. _Lemuroidea_, Lemurs
Order *s*. _Primates_, Monkeys, Apes, Man

PLANTS

I. THALLOPHYTA
- Class 1. **Algæ**, Seaweeds, etc.
- Class 2. **Fungi**, Mushrooms, etc.

II. BRYOPHYTA
- Class 1. **Anthoceroteæ**
- Class 2. **Hepaticæ**, Liverworts
- Class 3. **Musci**, Mosses

III. PTERIDOPHYTA
- Class 1. **Filices**, Ferns
- Class 2. **Rhizocarpeæ**, Pepperworts
- Class 3. **Equisetaceæ** (Calamaria), Horsetails
- Class 4. **Lycopodiaceæ**, Club-mosses

PHANEROGAMÆ, Flowering Plants

IV. GYMNOSPERMÆ
- Order *a*. *Cycadaceæ*, Cycads, Sago-palms
  (*_Cordaiteæ_)
- Order *b*. *Coniferæ*, Pines, Spruces, Cypresses, etc.

V. ANGIOSPERMÆ
- Class 1. **Monocotyledones**, Grasses, Lilies, Palms, etc.
- Class 2. **Dicotyledones**, Oaks, Elms, etc.

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An asterisk (*) after a page number indicates that a figure of the object named will be found on that page, while a dagger (†) implies that a definition or explanation is contained in the page designated, though this symbol is not employed unless there is more than one reference under a given head. Family and generic names of animals and plants are printed in *Italics*.

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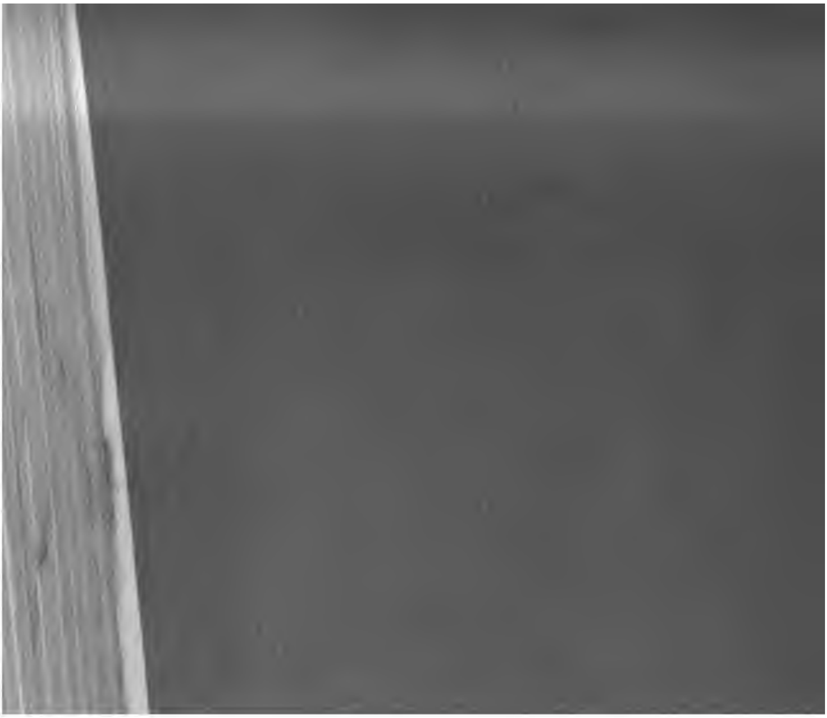

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